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BAMS

Bulletin of the American Meteorological Society

SMARTPHONE OBSERVING

MAKING NASA MORE RESILIENT

FLOODS FROM TROPICAL CYCLONES

Storms over Brazil

CHUVA and the Science of Tropical Clouds

BAMS

Bulletin of the American Meteorological Society

VOLUME 95, NUMBER 9, SEPTEMBER 2014

IN BOX

ARTICLES

ON THE COVER

Through multiple field campaigns in the diverse regional climates of Brazil, CHUVA aims to improve satellite precipitation estimation, nowcasting, cloud-resolving models, and the understanding of cloud electrification. For more information see the article by Machado et al. beginning on p. 1365. (Photo courtesy Jeferson Alves.)

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LETTER FROM THE EDITOR: CITIZEN SUDOKU

Years ago I fell for the quiet frustration of Sudoku. Eventually, however, penciling in puzzles became tedious—either too easy or too difficult to bother—and I stopped playing.

Thanks to an easy-to-use website, however, I recently was seduced again by these endlessly varied squares of numbers. The key was instant feedback. After proving to myself that I was still efficient, logical—just like old times—I clicked on a button labeled "How did I do?" It showed a distribution of results from other players: My time-to-finish lay far out in the tail of laggards. More than 90% of players had finished faster. Surely I could move up the curve! I was hooked immediately.

Purveyors of citizen science like Elmore et al. (p. 1335) also have discovered these twin necessities—easy use and instant feedback. Elmore et al. write that users of the mPING app for observing precipitation feel rewarded by seeing their data online and that their interest in weather increased when they watched reports being posted.

Mass and Madaus (p. 1343) see that the input from sensors on mobile computing devices and vehicles could increase hourly surface pressure data availability by 10,000-fold. Even this revolution requires minimal active citizen input, the motivation for public participation remains clear.

Still, those who play Sudoku understand a deeper motivation: actually doing science, even in abstraction. These puzzles are pure scientific thinking. When you prove a number goes somewhere by showing it can't go elsewhere, you're disproving a null hypothesis. Square by square you carefully lay one proof on top of another until you have created a whole edifice of "concepts."

Perhaps this is a future of citizen science—crowdsourcing abstract reasoning, not just observing. First recognize, as mPING developers did, the tasks that "require no advanced education in meteorology." Then, hopefully, tap into innate reasoning powers later.

But this potential for citizen science is subject to limitations that also apply to science for citizens. A Sudoku puzzle is a miniature of the climate modeling enterprise—an edifice layered concept by concept. The sum of limited procedures and processes blossoms into the entire Earth system. Yet Smith et al. (p. 1453) advocate a cultural overhaul of that process, reassembling those blocks of "datasets, algorithms, methods, models, and simulation architectures" from various research groups so that the uncertainties of results can more clearly be hierarchical and thus can better present uncertainties to decision makers. Smith et al. consider taking some of the resources now dedicated to pursuing research questions and trading it for better depictions of possibilities useful to citizens.

Meanwhile, Anderegg et al. (p. 1445) warn that scientists—the Sudoku masters themselves—don't always navigate their own puzzles successfully. In particular, climate scientists exhibit an "aversion" to overpredicting least likely outcomes. The scientists thus inadvertently shortchange the citizens who need to know the gamut of possibilities.

For citizen scientists, as well as science for citizens, participation is not enough. The logic itself constantly needs honing. The quality of the process of solving the puzzles, not just the instant feedback, will ultimately be a powerful motivation for, and proof of, success.

—*Jeff Rosenfeld,* Editor-in-Chief

ABSTRACTS

SOLAR COOKING IN THE SAHEL

Solar cookers have the potential to help many of the world's poorest people, but the availability of sunshine is critical, with clouds or heavy atmospheric dust loads preventing cooking. Using wood for cooking leads to deforestation and air pollution that can cause or exacerbate health problems. For many poor people, obtaining wood is either time-consuming or expensive. Where conflicts have led to displaced people, wood shortages can become acute, leading to often violent clashes between locals and refugees. For many refugee women, this makes collecting wood a high-risk activity.

For eight years, Agrometeorological Applications Associates and TchadSolaire (AAA/TS) have been training refugees to manufacture and use solar cookers in northeastern Chad, where there are more than 240,000 refugees. Solar cookers are cheap and simple to make. They are clean and safe, greatly reduce the need for wood, reduce conflicts, reduce the time girls spend collecting wood (thus favoring education), and allow pasteurization of water. Around 140,000 people in the area are now eating solar-cooked food.

Using long-term records of direct sunshine from routine surface measurements and aerosol retrievals from SEVIRI on board Meteosat, we present a climatology of conditions suitable for solar cooking in North Africa and West Africa. Solar cookers could be widely used, on an average of about 90% of days in some locations, with large seasonal and spatial variations from changing solar elevations, dustiness, and cloudiness. The climatology will facilitate the future distribution of solar cookers by organizations such as AAA/TS, who work using high-tech information to improve the lives of millions utilizing simple technologies. *(Page 1325)*

SATELLITE OBSERVATIONS FOR CMIP5: THE GENESIS OF OBS4MIPS

The objective of the Observations for Model Intercomparison Projects (Obs4MIPs) is to provide observational data to the climate science community, which is analogous (in terms of variables, temporal and spatial frequency, and periods) to output from the 5th phase of the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project (CMIP5) climate model simulations. The essential aspect of the Obs4MIPs methodology is that it strictly follows the CMIP5 protocol document when selecting the observational datasets. Obs4MIPs also provides documentation that describes aspects of the observational data (e.g., data origin, instrument overview, uncertainty estimates) that are of particular relevance to scientists involved in climate model evaluation and analysis. In this paper, we focus on the activities related to the initial set of satellite observations, which are being carried out in close coordination with CMIP5 and directly engage NASA's observational (e.g., mission and instrument) science teams. Having launched Obs4MIPs with these datasets, a broader effort is also briefly discussed, striving to engage other agencies and experts who maintain datasets, including reanalysis, which can be directly used to evaluate climate models. Different strategies for using satellite observations to evaluate climate models are also briefly summarized. *(Page 1329)*

MPING: CROWD-SOURCING WEATHER REPORTS FOR RESEARCH

The Weather Service Radar-1988 Doppler (WSR-88D) network within the United States has recently been upgraded to include dual-polarization capability. Among the expectations that have resulted from the upgrade is the ability to discriminate between different precipitation types in winter precipitation events. To know how well any such algorithm performs and whether new algorithms are an improvement, observations of winter precipitation type are needed. Unfortunately, the automated observing systems cannot discriminate between some of the more important types. Thus, human observers are needed. Yet, to deploy dedicated human observers is impractical because the knowledge needed to identify the various precipitation types is common among the public. To most efficiently gather such observations would require the public to be engaged as citizen scientists using a very simple, convenient, nonintrusive method. To achieve this, a simple "app" called mobile Precipitation Identification Near the Ground (mPING) was developed to run on "smart" phones or, more generically, web-enabled devices with GPS location capabilities. Using mPING, anyone with a smartphone can pass observations to researchers at no additional cost to their phone service or to the research project. Deployed in mid-December 2012, mPING has proven to be not only very popular, but also capable of providing consistent, accurate observational data. *(Page 1335)*

SURFACE PRESSURE OBSERVATIONS FROM SMARTPHONES: A POTENTIAL REVOLUTION FOR HIGH-RESOLUTION WEATHER PREDICTION?

Millions of smartphones possess relatively accurate pressure sensors and the expectation is that these numbers will grow into the hundreds of millions globally during the next few years. The availability of millions of pressure observations each hour from smartphones has major implications for high-resolution numerical weather prediction. This paper reviews smartphone pressure-sensor technology, describes commercial efforts to collect the data in real time, examines the implications for mesoscale weather prediction, and provides an example of assimilating smartphone pressure observations for a strong convective event over eastern Washington State. *(Page 1343)*

ENHANCING CLIMATE RESILIENCE AT NASA CENTERS: A COLLABORATION BETWEEN SCIENCE AND STEWARDSHIP

A partnership between Earth scientists and institutional stewards is helping the National Aeronautics and Space Administration (NASA) prepare for a changing climate and growing climate-related vulnerabilities. An important part of this partnership is an agency-wide Climate Adaptation Science Investigator (CASI) Workgroup. CASI has thus far initiated 1) local workshops to introduce and improve planning for climate risks, 2) analysis of climate data and projections for each NASA Center, 3) climate impact and adaptation toolsets, and 4) Center-specific research and engagement.

Partnering scientists with managers aligns climate expertise with operations, leveraging research capabilities to improve decision-making and to tailor risk assessment at the local level. NASA has begun to institutionalize this ongoing process for climate risk management across the entire agency, and specific adaptation strategies are already being implemented.

A case study from Kennedy Space Center illustrates the CASI and workshop process, highlighting the need to protect launch infrastructure of strategic importance to the United States, as well as critical natural habitat. Unique research capabilities and a culture of risk management at NASA may offer a pathway for other organizations facing climate risks, promoting their resilience as part of community, regional, and national strategies. *(Page 1351)*

THE CHUVA PROJECT—HOW DOES CONVECTION VARY ACROSS BRAZIL?

CHUVA, meaning "rain" in Portuguese, is the acronym for the Cloud Processes of the Main Precipitation Systems in Brazil: A Contribution to Cloud-Resolving Modeling and to the Global Precipitation Measurement (GPM). The CHUVA project has conducted five field campaigns; the sixth and last campaign will be held in Manaus in 2014. The primary scientific objective of CHUVA is to contribute to the understanding of cloud processes, which represent one of the least understood components of the weather and climate system. The five CHUVA campaigns were designed to investigate specific tropical weather regimes. The first two experiments, in Alcantara and Fortaleza in northeastern Brazil, focused on warm clouds. The third campaign, which was conducted in Belém, was dedicated to tropical squall lines that often form along the sea-breeze front. The fourth campaign was in the Vale do Paraiba of southeastern Brazil, which is a region with intense lightning activity. In addition to contributing to the understanding of cloud process evolution from storms to thunderstorms, this fourth campaign also provided a high-fidelity total lightning proxy dataset for the NOAA Geostationary Operational Environmental Satellite (GOES)-R program. The fifth campaign was carried out in Santa Maria, in southern Brazil, a region of intense hailstorms associated with frequent mesoscale convective complexes. This campaign employed a multimodel high-resolution ensemble experiment. The data collected from contrasting precipitation regimes in tropical continental regions allow the various cloud processes in diverse environments to be compared. Some examples of these previous experiments are presented to illustrate the variability of convection across the tropics. *(Page 1365)*

NORTH ATLANTIC TROPICAL CYCLONES AND U.S. FLOODING

Riverine flooding associated with North Atlantic tropical cyclones (TCs) is responsible for large societal and economic impacts. The effects of TC flooding are not limited to the coastal regions, but affect large areas away from the coast, and often away from the center of the storm. Despite these important repercussions, inland TC flooding has received relatively little attention in the scientific literature, although there has been growing media attention following Hurricanes Irene (2011) and Sandy (2012). Based on discharge data from 1981 to 2011, the authors provide a climatological view of inland flooding associated with TCs, leveraging the wealth of discharge measurements collected, archived, and disseminated by the U.S. Geological Survey (USGS). Florida and the eastern seaboard of the United States (from South Carolina to Maine and Vermont) are the areas that are the most susceptible to TC flooding, with typical TC flood peaks that are 2 to 6 times larger than the local 10-yr flood peak, causing major flooding. A secondary swath of extensive TC-induced flooding in the central United States is also identified. These results indicate that flooding from TCs is not solely a coastal phenomenon but affects much larger areas of the United States, as far inland as Illinois, Wisconsin, and Michigan. Moreover, the authors highlight the dependence of the frequency and magnitude of TC flood peaks on large-scale climate indices, and the role played by the North Atlantic Oscillation and the El Niño–Southern Oscillation phenomenon (ENSO), suggesting potential sources of extended-range predictability. *(Page 1381)*

THE DYNAMICS OF HURRICANE RISK PERCEPTION: REAL-TIME EVIDENCE FROM THE 2012 ATLANTIC HURRICANE SEASON

Findings are reported from two field studies that measured the evolution of coastal residents' risk perceptions and preparation plans as two hurricanes—Isaac and Sandy—were approaching the U.S. coast during the 2012 hurricane season. The data suggest that residents threatened by such storms had a poor understanding of the threat posed by the storms; they overestimated the likelihood that their homes would be subject to hurricane-force wind conditions but underestimated the potential damage that such winds could cause, and they misconstrued the greatest threat as coming from wind rather than water. These misperceptions translated into preparation actions that were not well commensurate with the nature and scale of the threat that they faced, with residents being well prepared for a modest wind event of short duration but not for a significant wind-and-water catastrophe. Possible causes of the biases and policy implications for improving hurricane warning communication are discussed. *(Page 1389)*

IMPACT OF TYPHOONS ON THE OCEAN IN THE PACIFIC: ITOP

Tropical cyclones (TCs) change the ocean by mixing deeper water into the surface layers, by the direct air–sea exchange of moisture and heat from the sea surface, and by inducing currents, surface waves, and waves internal to the ocean. In turn, the changed ocean influences the intensity of the TC, primarily through the action of surface waves and of cooler surface temperatures that modify the air–sea fluxes. The Impact of Typhoons on the Ocean in the Pacific (ITOP) program made detailed measurements of three different TCs (i.e., typhoons) and their interaction with the ocean in the western Pacific. ITOP coordinated meteorological and oceanic observations from aircraft and satellites with deployments of autonomous oceanographic instruments from the aircraft and from ships. These platforms and instruments measured typhoon intensity and structure, the underlying ocean structure, and the long-term recovery of the ocean from the storms' effects with a particular emphasis on the cooling of the ocean beneath the storm and the resulting cold wake. Initial results show how different TCs create very different wakes, whose strength and properties depend most heavily on the nondimensional storm speed. The degree to which air–sea fluxes in the TC core were reduced by ocean cooling varied greatly. A warm layer formed over and capped the cold wakes within a few days, but a residual cold subsurface layer persisted for 10–30 days. *(Page 1405)*

ERA-CLIM: HISTORICAL SURFACE AND UPPER-AIR DATA FOR FUTURE REANALYSES

Future reanalyses might profit from assimilating additional historical surface as well as upper-air data. In the framework of the European Reanalysis of Global Climate Observations (ERA-CLIM; www.era-clim.eu) project, significant amounts of pre-1957 upper-air and surface data have been cataloged (>2.5 million station days), imaged (>450,000 images), and digitized (>1.25 million station days) to prepare new input datasets for upcoming reanalyses. These data cover large parts of the globe, focusing henceforth on less well-covered regions such as the tropics, the polar regions, and the oceans and on very early twentieth-century upper-air data from Europe and the United States. The total numbers of digitized/inventoried records (i.e., time series of meteorological data at fixed stations or from moving observational platforms) are 80/214 (surface), 735/1,783 (upper air), and 61/101 [moving upper-air (i.e., data from ships, etc.)]. Here, the authors give an overview of the data rescue activities, the data, and the applied quality checking procedures and demonstrate their usefulness for analyzing past weather and climate. The data will be made available online (at www.era-clim.eu). The upper-air data will be included in the next version of the Comprehensive Historical Upper-Air Network (CHUAN) and are also available online (http://doi.pangaea.de/10.1594/PANGAEA.821222). *(Page 1419)*

THE CONCEPT OF ESSENTIAL CLIMATE VARIABLES IN SUPPORT OF CLIMATE RESEARCH, APPLICATIONS, AND POLICY

Climate research, monitoring, prediction, and related services rely on accurate observations of the atmosphere, land, and ocean, adequately sampled globally and over sufficiently long time periods. The Global Climate Observing System, set up under the auspices of United

CORRECTION

On p. 1076 of the July issue of *BAMS*, in the aticle "HyMeX: 10-Year Multidisciplinary Program on the Mediterranean Water Cycle" by P. Drobinski et al., a production error caused the caption for Fig. 9 to be placed under the image for Fig. 10 and the caption for Fig. 10 matched with the image for Fig. 9. *BAMS* apologizes for this error.

Nations organizations and the International Council for Science to help ensure the availability of systematic observations of climate, developed the concept of essential climate variables (ECVs). ECV data records are intended to provide reliable, traceable, observation-based evidence for a range of applications, including monitoring, mitigating, adapting to, and attributing climate changes, as well as the empirical basis required to understand past, current, and possible future climate variability. The ECV concept has been broadly adopted worldwide as the guiding basis for observing climate, including by the United Nations Framework Convention on Climate Change (UNFCCC), WMO, and space agencies operating Earth observation satellites.

This paper describes the rationale for these ECVs and their current selection, based on the principles of feasibility, relevance, and cost effectiveness. It also provides a view of how the ECV concept could evolve as a guide for rational and evidence-based monitoring of climate and environment. Selected examples are discussed to highlight the benefits, limitations, and future evolution of this approach.

The article is intended to assist program managers to set priorities for climate observation, dataset generation and related research: for instance, within the emerging Global Framework for Climate Services (GFCS). It also helps the observation community and individual researchers to contribute to systematic climate observation, by promoting understanding of ECV choices and the opportunities to influence their evolution. *(Page 1431)*

AWARENESS OF BOTH TYPE 1 AND 2 ERRORS IN CLIMATE SCIENCE AND ASSESSMENT

Treatment of error and uncertainty is an essential component of science and is crucial in policy-relevant disciplines, such as climate science. We posit here that awareness of both "false positive" and "false negative" errors is particularly critical in climate science and assessments, such as those of the Intergovernmental Panel on Climate Change. Scientific and assessment practices likely focus more attention to avoiding false positives, which could lead to higher prevalence of false-negative errors. We explore here the treatment of error avoidance in two prominent case studies regarding sea level rise and Himalayan glacier melt as presented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. While different decision rules are necessarily appropriate for different circumstances, we highlight that false-negative errors also have consequences, including impaired communication of the risks of climate change. We present recommendations for better accounting for both types of errors in the scientific process and scientific assessments. *(Page 1445)*

CHANGING HOW EARTH SYSTEM MODELING IS DONE TO PROVIDE MORE USEFUL INFORMATION FOR DECISION MAKING, SCIENCE, AND SOCIETY

New details about natural and anthropogenic processes are continually added to models of the Earth system, anticipating that the increased realism will increase the accuracy of their predictions. However, perspectives differ about whether this approach will improve the value of the information the models provide to decision makers, scientists, and societies. The present bias toward increasing realism leads to a range of updated projections, but at the expense of uncertainty quantification and model tractability. This bias makes it difficult to quantify the uncertainty associated with the projections from any one model or to the distribution of projections from different models. This in turn limits the utility of climate model outputs for deriving useful information such as in the design of effective climate change mitigation and adaptation strategies or identifying and prioritizing sources of uncertainty for reduction. Here we argue that a new approach to model development is needed, focused on the delivery of information to support specific policy decisions or science questions. The central tenet of this approach is the assessment and justification of the overall balance of model detail that reflects the question posed, current knowledge, available data, and sources of uncertainty. This differs from contemporary practices by explicitly seeking to quantify both the benefits and costs of details at a systemic level, taking into account the precision and accuracy with which predictions are made when compared to existing empirical evidence. We specify changes to contemporary model development practices that would help in achieving this goal. *(Page 1453)*

NOWCAST

NEWS AND NOTES

More Complete Rainfall Information for Climate Monitoring

Both satellite monitoring and ground-based measuring stations provide rainfall measurements, but data from these sources have limitations. For example, measurements derived from satellite data can be thrown off by complex terrain, and ground-based data can be limited by a lack of stations in some locations. Additionally, the information from the two sources has never before been integrated in a useful way. But a collaboration of researchers from the University of California, Santa Barbara (UCSB) and the United States Geological Survey (USGS) has produced a new blended dataset that combines worldwide rainfall measurements from both space and the ground to create data that can be utilized in environmental research as well as drought and famine early-warning efforts.

The Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset incorporates 0.05°-resolution satellite imagery with data from more than 50,000 ground-based rainfall stations to create gridded rainfall time series dating back to 1981. It "seeks to blend the best qualities of rainfall station observations, satellite temperature data, and rainfall's unique spatial characteristics to create the best available rainfall information for climate and agricultural monitoring," according to Gregory J. Husak of UCSB, who coauthored a recent USGS publication about CHIRPS.

Officials who monitor drought and rainfall can use the dataset for near-real-time, high-resolution data covering all longitudes and latitudes between 50°S and 50°N. The measurements can be incorporated into climate models to predict agricultural conditions. It has already been used to determine that rainfall in Kenya's Rift Valley in April of this year was the lowest in 34 years, thus preparing farmers there for drought conditions.

"The whole point of the dataset is to be able to take recent droughts and place them in a historical context," said Chris Funk of the USGS, who also coauthored the recent publication.

While the USGS is using CHIRPS to monitor specific drought-prone areas, researchers are also utilizing it to learn more about rainfall patterns worldwide. For example, the data suggest that decreased precipitation in the U.S. Southwest and eastern East Africa is "likely linked to warming in the western Pacific and eastern Indian oceans," explains Funk.

The CHIRPS dataset is available online at http://chg.geog.ucsb.edu/data/chirps/. [Sources: fondriest.com, University of California, Santa Barbara]

ECHOES

"This is really happening. There's nothing to stop it now."

—Thomas P. Wagner, NASA program scientist for the cryosphere, on the recent finding that large portions of the West Antarctica Ice Sheet (WAIS) have begun collapsing in what appears to be an irreversible trend exacerbated by climate change. A complete collapse of the WAIS could lead to a global sea level rise of up to 16 feet. Two recent studies, one published in *Science* and the other in *Geophysical Research Letters*, both found that naturally occurring warm water is being brought upward toward the ice sheet as stronger winds blow in the Antarctic region, creating a potentially catastrophic instability in the WAIS. One of the papers suggests this would result in the ice sheet melting into the Southern Ocean in the next 200–900 years. The intensification of winds around the Antarctic region has been linked by most scientists to anthropogenic climate change, although other influences could be natural or related to the Antarctic ozone hole. Regardless of the cause, the lead author of the *Science* article, Ian Joughin of the University of Washington, suggests that the demise of the ice sheet is unalterable, and that even a return of the melt rate to prior levels would be "too little, too late . . . [because] there's no stabilization mechanism."

[Source: *The New York Times*]

Local Factors Impact Decomposition More than Climate

Understanding how organic matter breaks down is important to climate science because decomposition is a vital part of the carbon cycle. Researchers have generally believed that climate is the most important influence on such decomposition, but a new study recently published in *Nature Climate Change* suggests that local factors such as animal populations and the abundance of soil fungi actually have a much greater impact than climate. The finding could help enhance climate projections.

"We're reaching the wrong conclusion about the major controls on decomposition because of the way we've traditionally collected and looked at our data," explains Mark A. Bradford of Yale University, lead author of the study. "That in turn will weaken the effectiveness of climate prediction."

To more accurately determine local effects on decomposition, a team of scientists scattered 160 blocks of wood from pine trees across five temperate forests in the eastern United States ranging from Connecticut to Florida, an area where the average annual temperature varies by about 11°C between north and south. While they chose similar forests for the study to concentrate on how climate impacts decomposition, they placed the wood blocks in differing kinds of terrain in order to also accurately represent the topographical variety of forests and spotlight local decomposition responses rather than regional factors.

"[W]e put some blocks on south-facing slopes, where they would be warmer in the summer, and others on north-facing slopes where it's colder," explains Bradford. "We put some on top of ridges and others next to streams where it was wetter."

The team then monitored the decomposition of the wood over a 13-month period and evaluated the climatic and local impacts by measuring how much carbon had been absorbed into microbes growing on the wood or released directly into the atmosphere as CO_2. They found that about 75%

of the variation in the decomposing wood could be attributed to local factors, and about 25% of the breakdown was from climatic factors. The study stated that most research investigating climate's influence on decomposition has used a mean response across regional and global areas, which according to the study's abstract can often be "irrelevant and misleading" and cause local factors to be overlooked.

According to Bradford, the findings suggest that in order to help climate modelers improve their models, "field ecologists like me [need] to go out and get much richer datasets with much more information" on other factors besides climate that play a role in decomposition.

"We shouldn't aggregate away information," Bradford says. "We should make measurements at those local scales to capture all of the importance [sic] processes that affect ecosystem functioning. Then the modelers will have far richer datasets to test their models against and see if they work." [Source: Yale University]

ON THE WEB

Crowdsourcing Storm Effects on Coastlines

Over the last 20 years, the U.S. Geological Survey (USGS) has compiled close to 150,000 aerial photographs of the Atlantic and Gulf coastlines taken after extreme storms. These high-resolution photos are captured from low altitudes and can be compared to earlier photos to identify changes in the coastline caused by the storms. The information can be used to elucidate the destructive effects of hurricanes and other storms and enhance predictive models of coastal erosion and damage.

However, according to Sophia Liu of the USGS, "[c]omputers cannot yet automatically identify damages and geomorphic changes to the coast from the oblique aerial photographs," so therefore "[h]uman intelligence is still needed to finish the job." Because the USGS does not have the personnel to study so many photos, they created a website called "USGS iCoast—Did the Coast Change?" (http://coastal.er.usgs.gov/icoast/about.php) to invite the public to assist. Visitors to the site can select random photos or choose specific locations from a map, and then compare pre- and poststorm images and identify changes to the coastline using predefined tag buttons.

Current mathematical models of coastal damage are developed from data on dune elevation and predicted wave action during storms. Adding information from volunteers visiting the website will aid in validating the models and improving damage predictions before future storms hit.

"After an event like Hurricane Sandy, there is always a great interest in our photographs," notes Barbara Poore of the USGS. "The USGS iCoast team hopes that people will [use the photos to] learn about coastal change and about their personal vulnerabilities to extreme storms." [Source: USGS]

ITCZ Most Sensitive to Out-of-Tropics Thermal Forcing

The intertropical convergence zone (ITCZ) is quite narrow, meaning that some of the rainiest spots in the tropics are located just a few hundred kilometers from the Earth's driest deserts. Small changes in the position of the ITCZ can thus greatly perturb local precipitation, so it is important to understand how the ITCZ might shift in response to heating anomalies. Many previous studies have demonstrated that the ITCZ can respond to heating well outside the tropics. For example, northern high-latitude cooling from either increasing Arctic sea ice cover or a weakened Atlantic thermohaline circulation shifts the ITCZ southward. Although high-latitude impacts on the ITCZ have been demonstrated by many studies, it is natural to expect tropical thermal forcing would be more effective at shifting the ITCZ. However, our research shows that high-latitude thermal forcing can actually cause a larger shift in the ITCZ than equivalent thermal forcing applied in the tropics.

We designed a series of model experiments to examine how effective thermal forcing in different latitude bands is at shifting the ITCZ. In aquaplanet simulations with the Geophysical Fluid Dynamics Laboratory (GFDL) Atmospheric Model, version 2 (AM2), heating is prescribed in the slab ocean lower boundary in the Northern Hemisphere, and cooling of equal magnitude is placed in the Southern Hemisphere. The meridional position of thermal forcing is systematically varied from the deep tropics to the high latitudes, while adjusting the maximum amplitude of the forcing to ensure that the total heating and cooling are the same in all cases.

In the absence of radiative feedbacks, tropical forcing is indeed more effective at shifting the ITCZ. This is because the impact of thermal forcing outside the tropics diminishes on its way toward the equator by quasidiffusive transport of energy. However, in AM2, cloud shortwave responses substantially amplify the effective strength of high-latitude thermal forcing. The applied ocean heating is accompanied by reductions in low cloud cover, thus resulting in a much larger temperature response in the extratropics, and a larger ITCZ shift. A theoretical framework based on energetics is useful to explain the degree of shifts.

Our study emphasizes the great importance of the high latitudes in determining the position of the ITCZ. Furthermore, the high-latitude influence on the tropics will become more significant in the future because the Arctic is expected to continue to warm much more rapidly compared to the rest of the globe as a result of anthropogenic climate change.—Jeongbin Seo (Ulsan National Institute of Science and Technology), S. M. Kang, and D. M. W. Frierson. *"Sensitivity of Intertropical Convergence Zone Movement to the Latitudinal Position of Thermal Forcing," in the April* Journal of Climate.

A GOOD SIGN FOR CLEANER AIR

If you're like most people, you probably consider billboards to be an eyesore—a kind of pollution, if you will. Researchers in Peru are attempting to turn that perception around by creating a billboard that scrubs air pollution out of the sky and coverts it to clean air. Created by researchers at Peru's University of Engineering and Technology (UTEC), the billboard uses an air filtration system that employs water to cleanse the dirty air, trapping pollutants in the water and allowing pristine air to be emitted back into the atmosphere. The first of the cleansing billboards is located in Lima, which according to World Meteorological Organization statistics has the highest air pollution levels in South America. The billboard can purify 100,000 cubic meters of air per day, which the researchers compare to the air-cleaning capacity of 1,200 mature trees. Along with removing common urban air pollution, the billboard is also able to absorb the various harmful dust, metal, and stone particles produced at construction sites, and it can even eliminate airborne bacteria. It has a cleaning radius of five city blocks and uses only 2.5 kilowatts of electricity per hour to operate—roughly equivalent to an emergency home generator. Scientists at UTEC previously developed a billboard in Lima that converted air into drinkable water.

New Thermometer Sets Standard for Accuracy

A thermometer has been developed that its creators say can measure temperature differences at unprecedented accuracy. The nano-Kelvin thermometer operates on the same principle behind the phenomenon known as the "whispering gallery," in which low-decibel sound travels along the curve of an elliptical space and returns audibly to the spot from where it originated (for example, at St. Paul's Cathedral in London). In this case, beams of red and green light are injected into a spinning crystalline disk, where they race around the edge thousands of times. When the crystal is heated, it expands, causing the speeds of the two colors to change depending on the temperature of the crystal. Measuring the relative differences between those speeds can yield temperature changes within the disk to 30 billionths of a degree. By comparison, previous light-based thermometers only measured changes to 100 billionths of a degree.

"To emphasize how precise this is, when we examine the temperature of an object we find that it is always fluctuating," explains the University of Adelaide's Andre Luiten, coauthor of a paper on the thermometer recently published in *Physical Review Letters*. "We all knew that if you looked closely enough you find that all the atoms in any material are always jiggling about, but we actually see this unceasing fluctuation with our thermometer, showing that the microscopic world is always in motion."

While it is possible to take even more precise temperature readings in cryogenic environments near absolute zero, "[w]e believe this is the best measurement ever made of temperature—at room temperature," states Luiten. He notes that the methodology behind the thermometer could be used for other types of sensitive measurements, such as pressure and humidity. [Source: University of Adelaide]

Remotely Sensed CO_2 Emissions Show Promise for Satellite Measurements

Keeping track of CO_2 emissions from power plants can be complicated due to discrepancies in data that are made public by individual countries. A new study in the *Proceedings of the National Academy of Sciences* highlights the increasing potential of space-based monitoring of emissions, suggesting that satellite-based measurements may soon help with the oversight of emissions regulations.

The research utilized ground-based remote spectrometers—the kinds of instruments found on satellites—and point sensors to measure and compare emissions from two coal-fired power plants in northwest New Mexico over a four-month period. The spectrometers observed plumes of CO_2 and other pollutants in the entire atmospheric column above the plants—just as satellite-based spectrometers would when looking down on Earth. And while past satellite measurements have been problematic because of limited range and low resolution, the new study successfully verified its total-column measurements against in situ observations by in-stack sensors at the power plants.

The measurements "provide a metric to examine and assess future satellite-monitoring strategies," says study coauthor

Manvendra Dubey of Los Alamos National Laboratory. Such space-based verification is favored over emissions data as the most effective way to accurately and uniformly measure carbon output across the globe. In some countries, data reports are unreliable; in China, for example, "provincial and national CO_2 emissions do not agree," notes Dubey. "There is a large gap between the two. We need to know which is right for accurate accounting and future targets."

The study also showed that 70%–75% of the atmosphere within about a 6-mile region of the two plants—San Juan Generating Station and Four Corners Generating Station—is polluted with their emissions. [Source: Climate Central]

ECHOES

"This is unique in my experience."

—Matt Crowther, senior meteorologist for The Weather Channel and an experienced storm chaser, commenting on the simultaneous occurrence of two intense tornadoes in Pilger, Nebraska, in mid-June. While twin tornadoes have been documented periodically—one such incident in 1965 left 14 people dead in Indiana—the size, strength, and lifespan of both Nebraska twisters set them apart from most other incidences of dual tornadoes. "In all other cases I have seen, one tornado may last for a little while fairly close to another, but nothing like what happened [in Nebraska]," Crowther noted. At press time, scientists were still trying to determine what caused the twin vortexes, with some suggesting occlusion—in which the initial tornado is surrounded by cool, dry air and usually (but not always) weakens while nearby the same supercell thunderstorm has enough energy for another twister to form where the environment is still favorably warm and moist. Another theory was that the tornado's main vortex broke down into equally large and powerful vortexes, while others speculated that the twisters came from two entirely separate supercells. Whatever the cause of the tornadoes—which killed two and injured dozens—most scientists agreed that the event was highly unusual. "I've seen all sorts of weather, but I've never seen the data for two tornadoes at the same time like this," said Jeff Weber, who has worked at UCAR for 16 years. [Sources: weather.com, NBC News]

SOLAR COOKING IN THE SAHEL

BY BETH NEWTON, SOPHIE COWIE, DEREK RIJKS, JAMIE BANKS, HELEN BRINDLEY, AND JOHN H. MARSHAM

FIG. 1. A solar cooker in use in Chad. Foil glued to cardboard reflects energy onto a darkened cooking pot placed inside a clear plastic bag, cooking even dried food in around 3 h.

EXISTING USE OF SOLAR COOKERS IN THE SAHEL. Solar cookers cook food by focusing direct-beam solar energy. Figure 1 shows a simple cooker consisting of aluminum foil glued onto a cardboard panel and a dark cooking pot contained in a clear plastic bag to retain the warm air. Such a cooker can cook even dried food in less than three hours as long as sunshine is available, allowing morning cooking of the midday meal and afternoon cooking of the evening meal (which can be kept warm in simple thermos bags made from waste materials).

Agrometeorological Applications Associates and TchadSolaire (AAA/TS) have been training refugees and the indigenous population in Chad to use and manufacture solar cookers since 2005. In several camps, teams of refugee women now handle most of the maintenance and furnishing of cookers, training, and finance (including the impending contributions under the Carbon Credit scheme that will initially cover about 40,000 families). According to data from AAA/TS, wood is still needed for the early morning meal for children (about 12% of traditional daily energy needs) for about 20–30 days per year when dust prevents solar cooking, and for afternoon cooking during the rainy season (also about 20–30 days per year).

The program has support from the Government of Chad, in the context of its actions to preserve the environment. It has also found, gradually, total approval—and indeed, enthusiasm—from men. The sharing of knowledge with the surrounding population, and the distribution of cookers to them, has greatly reduced conflicts. Key to acceptance is that solar energy is freely and equitably distributed. The program has a positive effect on six of the eight UN millennium goals (www.un.org/millenniumgoals/) and is neutral for the other two. Solar cookers are therefore a cheap, practical tool for sustainable development, which can be built and main-

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tained without access to expensive tools or machinery. Planning of expansion of solar cooking to other regions in northern Africa would be facilitated by a more precise assessment of the availability of direct solar energy.

A CLIMATOLOGY FOR SOLAR COOKING.

Solar cookers require direct sunshine for effective cooking, so clouds or heavy atmospheric dust loads can slow down or prevent their use. Surface meteorological ("SYNOP") stations record the daily hours of direct sunshine (exceeding 120 W m^{-2}, with a resolution of 0.1 h) and were used to generate a climatology of days with greater than 6 h available for cooking ("cooking days"; locations of SYNOPs used are shown in supplementary Fig. ES1). SYNOP station records of sunshine hours are often made using Campbell-Stokes sunshine recorders. Scattered clouds can give errors of up to 20% for these data, and due to humidity the threshold for recording direct sunshine can vary from 70 to 280 W m^{-2}. However, in the dry areas suitable for solar cooking we do not expect large threshold variations, and we expect errors from dew and frost to be negligible.

The SYNOP dataset is very sparse in many parts of Africa and therefore is complemented by the use of geostationary satellite data. Various climatologies of surface solar radiation already exist (e.g., NASA GEWEX surface radiation budget data, ISCCP FD RadFlux and NASA/LaRC surface meteorology and solar energy data). However, these have a temporal resolution of at best three hours and extend, at present, only to June 2007 (at the latest). Higher temporal resolution surface insolation records are derived from SEVIRI (Spinning Enhanced Visible and Infrared Imager) on board the Meteosat Second Generation satellite series by EUMETSAT's Land Satellite Application Facility, but the approach uses a fixed aerosol climatology. Therefore, to obtain a climatology that accounts for subdaily variability in dust and cloud amount, we make use of a high temporal resolution record of aerosol optical depths (AODs) derived from SEVIRI.

Direct surface solar irradiance was derived using the Beer-Lambert law using AODs retrieved from SEVIRI. AOD retrievals are performed for land pixels designated as cloud-free, for solar zenith and view angles less than 70°, and were made available for this study for the period 2008–12, at a half-hourly time resolution between 0600 and 1600 UTC. The mean monthly percentages of "cooking days" were found from these data. Since SEVIRI AODs were only available between 0600 and 1600 UTC, there are some locations and periods that have solar zeniths less than 70° that are missing in the AOD record. Here, cooking hours were simply scaled to allow for these missing periods.

To assess the validity of the monthly-mean cooking days from SEVIRI, Fig. 2 shows a comparison with the SYNOP results with the best-fit straight line shown. Locations on coasts and rivers (where subpixel inhomogeneity is likely to be the cause of apparently excessive cloud flagging) and at high latitudes during December (where there are insufficient retrievals for good comparison) were excluded. Results from the two methods are reasonably well correlated (correlation coefficient of 0.52), but means from SEVIRI are lower than from surface observations, particularly for lower values. This systematic difference cannot be explained by typical errors in SYNOP data or SEVIRI AODs, and is likely mainly due to the cloud masking of SEVIRI; optically thin and partial cloud cover in the SEVIRI pixel is likely masked in the satellite data, while having minimal or no effect on the surface observations, and our analysis suggests some excessive cloud masking persists around areas such as coasts and rivers. SEVIRI AODs are also only retrieved for solar zeniths less than 70°, whereas surface observations are continuous. Figure 2 shows that although absolute values from SEVIRI are biased low, we expect SEVIRI to be valuable for examining spatial and temporal variations in cooking days.

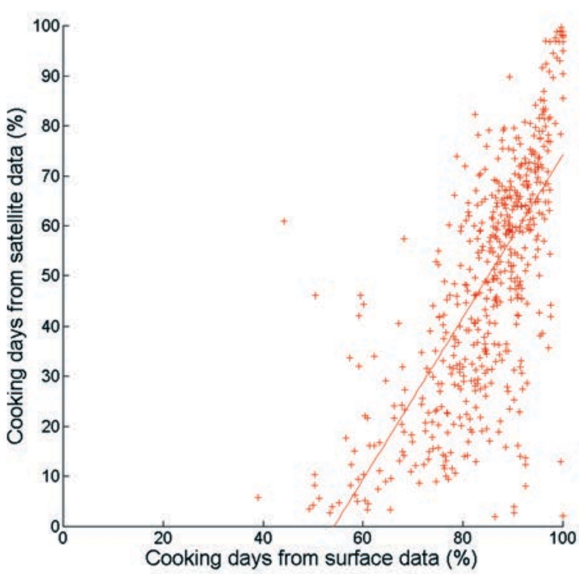

Fig. 2. Comparison of monthly means of the percentage of days with at least 6 h with > 120 W m^{-2} of direct solar irradiance ("cooking days") observed at surface stations and calculated from cloud-free SEVIRI AODs. As expected, SEVIRI gives lower values than the surface observations (see text).

Figure 3 shows the annual mean percentage of cooking days, along with monthly means from July and January, from both SEVIRI and surface observations in the Sahel (other months are shown in supplementary Figs. ES2–ES4). Consistent with the practical experience of AAA/TS, Fig. 3 shows 80% to almost 100% of days in northern Chad can be classified as "cooking days." Figures 3b, d, and f allow a station-by-station comparison of SEVIRI with SYNOP data. Consistent with Fig. 2, where SEVIRI reports low values, SYNOP values are significantly higher, but the spatial patterns are similar in each dataset. We note two additional caveats of SEVIRI. Validation indicates that its capabilities are strongest over drier and less vegetated surfaces such as those found in the Sahara and Sahel. Biomass-burning aerosol may be significant over the Sahel in winter, and SEVIRI AODs may miss this unless it is masked as cloud, although here SYNOP values are still greater than those from SEVIRI.

There are three main factors affecting whether cooking is possible: solar geometry, clouds, and dust. In boreal winter, the greater solar irradiance in lower latitudes is a strong control (Fig. 3e), whereas in boreal summer (Fig. 3c), clouds associated with the West African monsoon dominate and often prevent cooking in many regions south of 15°N. Summertime

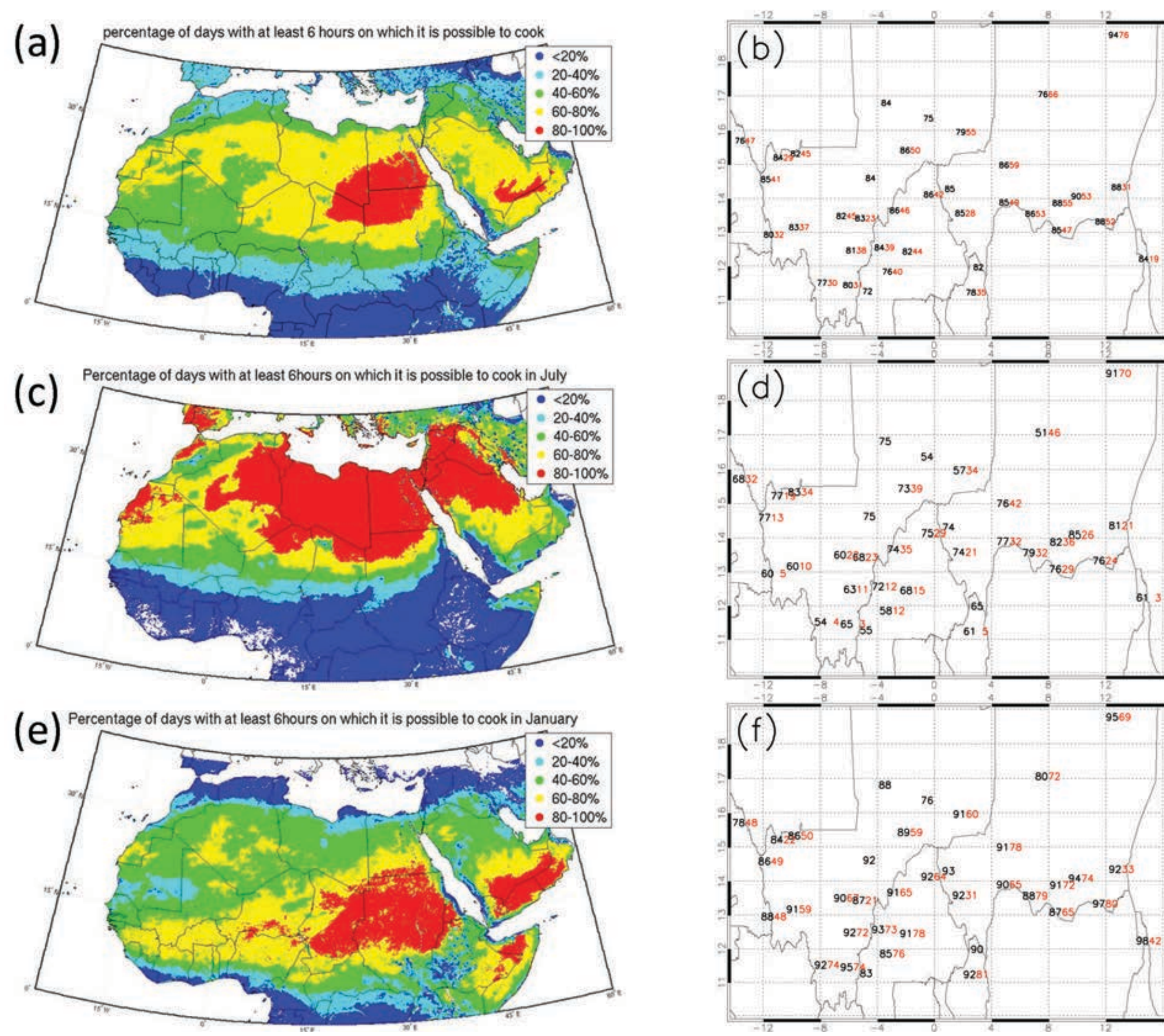

Fig. 3. Mean percentage of days with more than 6 h with direct solar irradiance >120 W m^{-2} ("cooking days") during (a,b) the whole year, (c,d) Jul, and (e,f) Jan. (a), (c), and (e) show results calculated from SEVIRI AODs and cloud mask. (b), (d), and (f) show results from surface observations (red) and closest SEVIRI pixel (black). Note that for clarity these only show surface stations in the Sahel area and not all the surface stations used in Fig. 2 (i.e., not those in Libya, Tunisia, Egypt, Chad, and Mauritania; see Fig. ES1 in online supplement).

clouds also affect cooking in the Atlas Mountains and around the coasts of the Arabian Peninsula (although many daylight hours were missing in Arabia, so the scaling correction there was significant). In January, clouds are mainly a problem close to the equator and the Intertropical Convergence Zone, in the Ethiopian highlands, and in Europe. Dust loads over Arabia and the Sahara are highest in summer (in the Sahara centered close to 0°W in July), and this reduces cooking days there. In winter, the Bodélé depression (around 17°N, 19°E) is more dominant, and downwind of this feature cooking hours in January are reduced (Fig. 3e). The cooking minimum in Mauritania (around 20°N, 10°W) is consistent with dust sources shown in Prospero et al. (2002). The Nile is easily identified in Egypt and Sudan in the SEVIRI plots; this is likely from persistent cloud-flagging errors as well as real clouds.

The annual mean in cooking days (Figs. 3a, b) reflects the balance between solar geometry, clouds, and dust. The maximum is located in the northeast Sahara away from monsoon and midlatitude clouds and the main dust maxima. Through the year, solar cookers can be used for at least 6 h (approximately two meals) for more than 80% of days over wide areas, and often more than 90% of days, although values are greatest in desert regions and the northern Sahel, where civil population densities are low. Values are lower where greater populations are made more viable by increased cloudiness and rain. However, many of the most vulnerable people are located close to the desert margins, where solar cooking is most practical (e.g., the refugee camps of northern Chad, where AAA/TS have ongoing projects). Furthermore, since in the Sahel cloudiness is maximized late in the day, 50% of days are "cooking days" even at 12°N in July (Fig. 3d).

CONCLUSIONS AND OUTLOOK. This first climatology of sunshine derived for solar cooking shows it can be the main cooking method for many vulnerable and other people and a useful method of cooking in areas such as the summertime Sahel, where clouds and dust reduce hours of direct sunshine. This climatology of sunshine from SEVIRI and SYNOPs has a number of practical implications beyond solar cooking—for example, it could be used to examine the feasibility of solar electricity generation.

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FOR FURTHER READING

Banks, J. R., and H. E. Brindley, 2013: Evaluation of MSG-SEVIRI mineral dust retrieval products over North Africa and the Middle East. *Remote Sens. Environ.*, **128**, 58–73, doi:10.1016/j.rse.2012.07.017.

——, ——, C. Flamant, M. Garay, N.-C. Hsu, O. V. Kalashnikova, L. Kluser, and A. Sayer, 2013: Intercomparison of satellite dust retrieval products over the West African Sahara during the Fennec campaign in June 2011. *Remote Sens. Environ.*, **136**, 99–116, doi:10.1016/j.rse.2013.05.003.

Brindley, H. E., and J. E. Russell, 2009: An assessment of Saharan dust loading and the corresponding cloud-free longwave direct radiative effect from geostationary satellite observations. *J. Geophys. Res.*, **114**, D23201, doi:10.1029/2008JD011635.

Coulson, K. L., 1975: *Solar and Terrestrial Radiation: Methods and Measurements*. Academic Press, 322 pp.

Haywood, J. M., and Coauthors, 2008: Overview of the dust and biomass-burning experiment and African monsoon multidisciplinary analysis special observing period-0. *J. Geophys. Res.*, **113**, D00C17, doi:10.1029/2008JD010077.

Ikdea, H., T. Aoshima, and Y. Miyake, 1986: Development of a new sunshine-duration meter. *J. Meteor. Soc. Japan*, **64**, 987–993.

Marsham, J. H., and Coauthors, 2013: Meteorology and dust in the central Sahara: Observations from Fennec supersite-1 during the June 2011 Intensive Observation Period. *J. Geophys. Res.*, **118**, 1–21.

Prospero, J. M., P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill, 2002: Environmental characterization of global dust sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Rev. Geophys.*, **40**, doi:10.1029/2000RG000095.

Stein, T. H. M., D. J. Parker, J. Delanoë, N. S. Dixon, R. J. Hogan, P. Knippertz, and J. H. Marsham, 2011: Vertical cloud structure for the West African monsoon: A four-year climatology using CloudSat and CALIPSO. *J. Geophys. Res.*, **116**, D22205, doi:10.1029/2011JD016029.

Yang, G.-Y., and J. Slingo, 2001: The diurnal cycle in the Tropics. *Mon. Wea. Rev.*, **129**, 784–801, doi:10.1175/1520-0493(2001)1292.0.CO;2.

Satellite Observations for CMIP5

The Genesis of Obs4MIPs

BY JOAO TEIXEIRA, DUANE WALISER, ROBERT FERRARO, PETER GLECKLER, TSENGDAR LEE, AND GERALD POTTER

BACKGROUND. Global climate modeling systems are the essential tools that provide climate projections. Observations play an essential role in the development and evaluation of these climate modeling systems. In particular, observations from satellite platforms often provide a global depiction of the climate system that is uniquely suited for these purposes.

The initial goal of the Observations for Model Intercomparison Projects (Obs4MIPs), launched by NASA and the U.S. Department of Energy (DOE), is to better exploit existing satellite measurements by making them more accessible for research involving the fifth phase of the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project (CMIP5)[1]. CMIP5 specifies a series of standard experimental protocols that facilitate the community-based study of coupled Earth system model simulations, and has been a centralizing resource for the Intergovernmental Panel on Climate Change Working Group I contribution to the Fifth Assessment Report (IPCC WGI AR5) and Summary for Policy Makers.

[1] Information about CMIP5 (WCRP Coupled Model Intercomparison Project—Phase 5) can be found in the Special Issue of the *CLIVAR Exchanges Newsletter*, No. 56, Vol. 15, No. 2.

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In a 2012 *BAMS* article, Taylor and colleagues describe in detail the protocol for CMIP5, which defines the scope of simulations that were undertaken by the participating modeling groups. For several of the prescribed retrospective simulations (e.g., decadal hindcasts, AMIP, and twentieth-century coupled simulations), observational datasets can be used to evaluate and diagnose the simulation outputs.

A broad range of observational datasets is used for climate model evaluation. The Obs4MIPs project was launched making selected NASA datasets more readily accessible for CMIP5 research, and efforts have been underway to enable other agencies and data experts to contribute well-established products with demonstrated value for model evaluation (see Summary below). Enthusiastic support for the project has been expressed by the WCRP's Data Advisory Council and via recommendations of a recent international workshop targeting systematic errors in climate models (www.metoffice.gov.uk/media/pdf/h/9/WGNE_Workshop_Summary_v1p0.pdf).

APPROACH. Given the importance of observations to the model evaluation process, along with the range and complexity of the observational datasets needed for a robust assessment, a simple framework to identify, organize, and disseminate them for CMIP5 was created by Obs4MIPs.

The CMIP5 simulation protocol is utilized as a strict guideline for deciding which observations to stage in parallel to the model simulations—in particular: which variables, and for what periods, temporal frequencies, and spatial resolutions. Figure 1 illustrates the essence of the approach: The goal is to use the CMIP5 simulation protocol, produced by the WCRP's Working Group on Coupled Modeling (WGCM), which organizes climate model intercomparisons (top path in figure) to select the satellite observations that constitute the datasets being put together in this project and create a parallel path for the observations (bottom path in figure).

The main tasks of Obs4MIPs are to

1) engage with the climate modeling, observational, and analysis communities to identify potential observational datasets for model evaluation and diagnostics, strictly following the CMIP5 protocol document;
2) work with the observational teams to establish the necessary metadata information for the candidate observational datasets while documenting as best as possible the relative quality of the observations and their applicability for direct comparison to model quantities, and produce a technical document addressing these issues;
3) enable the observational science teams to facilitate production of the identified datasets, with the needed characteristics (variables, periods, resolutions) and formats [e.g., adhering to the Climate-Forecast (CF) metadata convention as applied in CMIP5]; and
4) organize and disseminate these datasets in a manner that closely parallels the model data archive.

DATA. The goals for the tasks described above were achieved for the initial datasets by directly involving the NASA science teams responsible for the relevant observational datasets. A variety of satellite data products were considered. It was felt that for a successful outcome of the first phase of this project it was more important to produce a relatively small but reliable set of observational products. Essentially all of the selected products have been publicly available for some time, but have not historically been tailored for a direct comparison with climate models with respect to output statistics, format, and metadata information.

Table 1 highlights the initial Obs4MIPs datasets that were available with documentation when this paper was submitted. The initial datasets include key climate variables that are being routinely produced from space-based observational systems such as atmospheric temperature profiles from the Atmospheric Infrared Sounder (AIRS) and the Microwave Limb Sounder (MLS) instruments; specific humidity profiles from AIRS and MLS; mole-fraction of ozone from the Tropospheric Emission Spectrometer (TES); sea surface temperature from the Advanced Microwave Scanning Radiometer (AMSR-E); top-of-the-atmosphere longwave and shortwave radiation from the Clouds and the Earth's

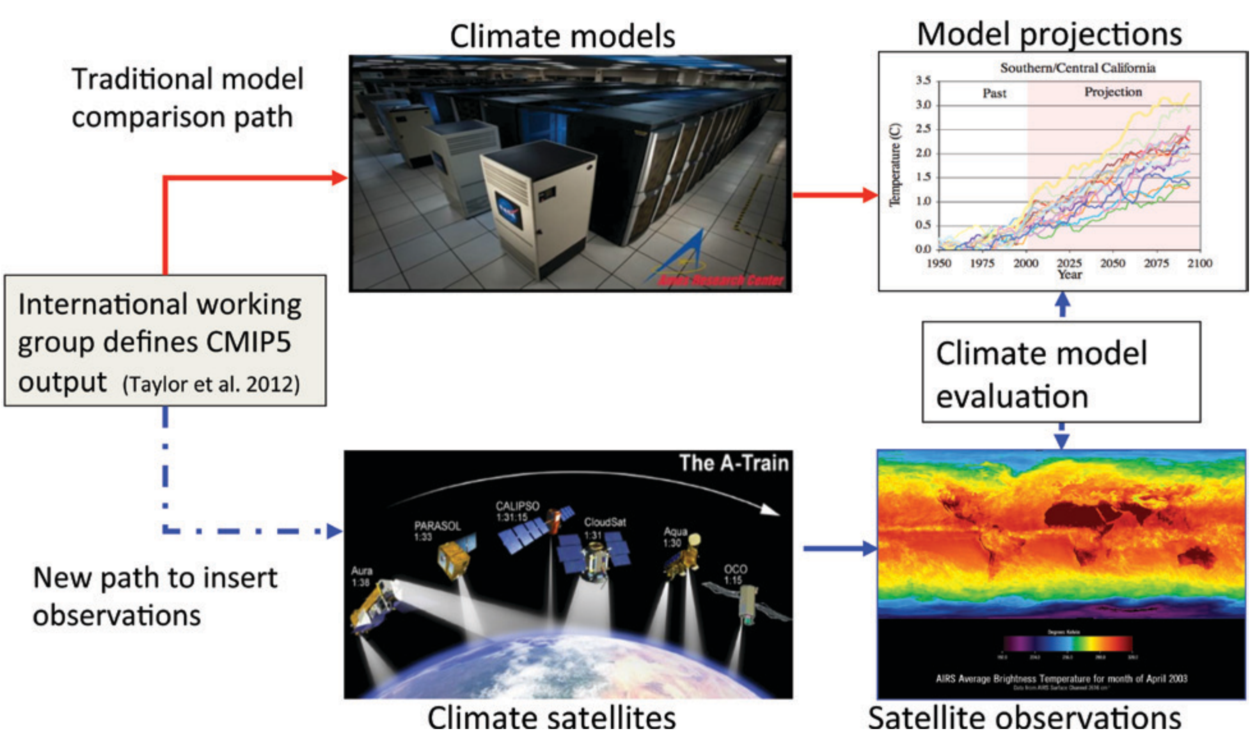

Fig. 1. Schematic showing the essence of the Obs4MIPs approach: to use the CMIP5 simulation protocol, produced by WGCM, which organizes climate model intercomparisons (top path), to select the satellite observations that are in the Obs4MIPs project and create a parallel path for the observations (bottom path).

Radiant Energy System (CERES) instrument; total cloud fraction from the Moderate Resolution Imaging Spetro-radiometer (MODIS); AVISO sea surface height from the TOPEX and JASON instruments; total surface precipitation from the Tropical Rainfall Measuring Mission (TRMM); and the 10-m (above the surface) wind over the ocean from QuikSCAT. More recent additions and planned contributions to Obs4MIPs are summarized in the Summary below.

This initial set of satellite observations—which is expected to grow over time—is directly accessible from the Earth System Grid Federation (ESGF) supporting CMIP, providing a readily accessible and focused resource for climate model evaluation. A first set of Obs4MIPs datasets and corresponding technical documents can be obtained at http://esg-datanode.jpl.nasa.gov/esgf-web-fe/.

A particularly important component of Obs4MIPs is the production of technical documentation synthesizing the most essential information needed by the researchers that will analyze the models and the observations. These documents have been produced (often one per variable), and basically contain detailed information about the data field and data origin (e.g., "measurement-to-product" processing), validation and uncertainty estimates, considerations for model–observation comparisons (e.g., sampling biases), the instrument overview, and finally, key references and points of contact.

EVALUATING CLIMATE MODELS WITH OBSERVATIONS: A BROADER PERSPECTIVE AND DISCUSSION. Up to this point, we have concentrated our discussion on satellite observations. A key reason is the fact that, to a good approximation, measurements made from satellite platforms are global in nature. However, it is envisioned that the strict metadata and data constraints applied to CMIP5 will be generalized to facilitate the inclusion of in situ data within Obs4MIPs. As a test case, multiyear measurements of atmospheric structure at specific fixed locations have been made available, including from the DOE's Atmospheric Radiation Measurement (ARM) program "best estimates" (ARMBE) of key observables at selected ARM sites. In fact, one of the more novel aspects of the CMIP5 output, coordinated with the Cloud Feedback Model Intercomparison Project (CFMIP),

Table 1. Initial set of obs4MIPs published and documented datasets (at date of submission). The datasets are 1 × 1 degree Lat-Lon monthly averages, with global coverage, unless otherwise noted. The temperature, specific humidity, and ozone datasets are also vertically stratified at the CMIP5 required pressure levels.

Data source	CMIP5 protocol variables	Time period (month/year)	Comments
AIRS (≥ 300 hPa)	Atmospheric temperature, specific humidity (*ta, hus*)	9/2002–5/2011	AIRS + MLS needed to cover all CMIP5 required pressure levels
MLS (< 300 hPa)	Atmospheric temperature, specific humidity (*ta, hus*)	8/2004–12/2010	2 × 5 degrees Lat-Lon AIRS + MLS needed to cover all CMIP5 required pressure levels
TES	Mole fraction of ozone (*tro3*)	7/2005–12/2009	2 × 2.5 degree Lat-Lon
AMSR-E	Sea surface temperature (*tos*)	6/2002–12/2010	
CERES	Top-of-the-atmosphere outgoing longwave and shortwave radiation, incident shortwave radiation fluxes (*rlut, rlutcs, rsut, rsutcs, rsdt*)	3/2000–6/2011	
MODIS	Total cloud fraction (*clt*)	3/2000–9/2011	
TOPEX/JASON series	Sea surface height above geoid (*zos*)	10/1992–12/2010	AVISO Product
TRMM	Precipitation flux (*pr*)	1/1998–6/2011	0.25 × 0.25 degree, 50°N–50°S Monthly averages and 3-hourly snapshots
QuikSCAT	Near-surface (10-m) winds (*sfcWind, uas, vas*)	8/1999–10/2009	Oceans only, excluding sea ice regions.

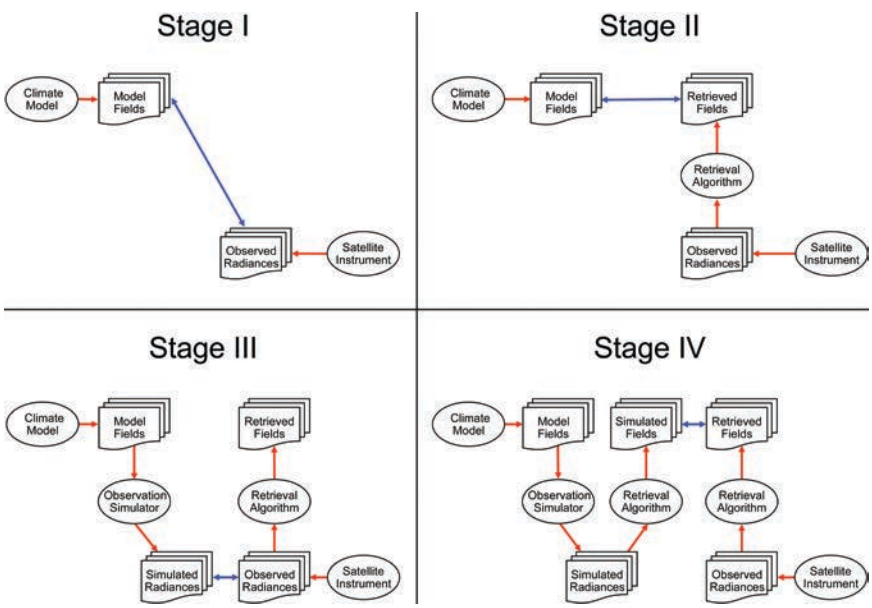

Fig. 2. The four stages of model vs satellite observations comparison.

is the high-frequency archiving of selected quantities at several locations around the globe (including the ARM locations).

In a related effort, selected output from the major analysis and reanalysis products is being made available in a similar manner to Obs4MIPs. Analyses are optimal combinations of observations and complex dynamical models, which while suffering from shortcomings inherent to the dynamical model, data-assimilation method, and the quantity and quality of the observations used, are often capable of producing high-quality products associated with variables that tend to be difficult to produce directly from satellite-based measurements.

Initial reanalysis products (currently available via ESGF under the project name "Ana4MIPs") consist of monthly averaged output provided from NASA's Modern Era Retrospective Analysis (MERRA), with plans to include NOAA's Climate Forecast System Reanalysis (CFSR) and twentieth-century Reanalysis (20CR), the European Center for Medium-range Weather Forecasts Interim reanalysis (ECMWF-Interim), and the Japanese Meteorological Agency (JMA) 25-year Reanalysis (JRA-25). These datasets are being published on ESGF in a similar way to CMIP5 and Obs4MIPs.

The evaluation and diagnostics of climate models using complex observations such as the ones produced from satellite remote sensing is a field that is growing in sophistication. The current Obs4MIPs, and companion efforts such as one by the CFMIP community (CFMIP-OBS; http://climserv.ipsl.polytechnique.fr/cfmip-obs/), are the initial steps in a long-term effort to bring together expertise in climate modeling and observations to improve climate projections. We anticipate that for future climate-model intercomparison endeavors, the observational community will play a larger role in helping to define the requirements for the model intercomparison output; in fact, a workshop is currently being organized with the goal of improving the use of satellite data for the next-generation model intercomparison, CMIP6. In this context, some efforts, including CFMIP-OBS, are trying to go beyond a more traditional comparison between model output and observationally derived (retrieved) geophysical variables using what is often referred to as "observation simulators."

These efforts could be thought of as part of a more comprehensive process that is depicted in Fig. 2, where four different stages of model-observation comparison are illustrated in a simple manner. Stage I refers to the very early efforts, when model-derived quantities (e.g., temperature) could not be directly compared to satellite-observed quantities (e.g., radiances as in Fig. 2). The traditional approach, illustrated in stage II, involves the development of retrieval algorithms that attempt to solve the problem of obtaining geophysical variable values from directly measured quantities (e.g., from radiances to temperatures). As mentioned, recent efforts have moved the field to stage III, where observation simulators attempt to simulate the quantities directly measured by satellite instruments from model-derived geophysical quantities (e.g., from model temperature to model radiances). Many of these efforts have an origin in modern data-assimilation (for numerical weather prediction) systems that assimilate radiances directly by using observation simulators (also known as "forward models" or "forward operators"). A final stage IV is achieved when observation simulators and retrieval algorithms are combined on the modeling side to produce a model-derived geophysical variable that mimics as much as possible the measurement/retrieval procedure, which would help us to understand the uncertainties of models and observations in "model space." Stage IV allows for the comparison between geophysical variables from both the modeling and the observational systems, which is often more intuitive to analyze than a comparison in "observation space." Although the decision concerning which stage needs to be attained in a particular model–observation comparison will depend on a variety of factors (e.g., what is the specific process being investigated? Which observational system is being used?), it is clear that any future efforts in this exciting and growing field of model evaluation with satellite observations will be at one of the stages of this diagram.

SUMMARY. In this short paper, the Obs4MIPs project is summarized. The main goal of Obs4MIPs is to serve the climate-science community that will analyze CMIP5 simulations by facilitating the accessibility to well-established observational products, specifically those suited for model evaluation. The essence of the method devised to achieve this goal is to strictly follow the CMIP5 protocol document (Taylor et al. 2012) that specifies the output for the CMIP5 simulations (e.g., variables, statistics, metadata). By following this document, it was possible to create a fairly small (compared to the large variety of climate-related observational datasets in existence) set of satellite observations that strictly comply with the output demands of the climate-model simulations. The different mission and instrument projects responsible for these specific observations have been heavily involved in the processing of the Obs4MIPs datasets and the elaboration of the accompanying technical documents that describe the key aspects of each product. The Obs4MIPs data are available from the ESG websites accessible from PCMDI, the Jet Propulsion Laboratory (JPL), and the other ESGF gateways.

At the time of the final version of this paper (late 2013), a variety of additional datasets have been added to Obs4MIPs, including: Aerosol optical depth over land from the Multiangle Imaging SpectroRadiometer (MISR) and over ocean from MODIS, CERES surface radiation budget, Leaf Area Index (LAI) from MODIS, and a number of satellite simulator products contributed by CFMIP-OBS. The NASA Science Working Group has also recommended including the MODIS-derived snow cover product, and the NOAA National Snow & Ice Data Center (NSIDC) sea ice concentration climate data record.

One important challenge during this first phase of Obs4MIPs has been the selection of data among different observational products that may produce similar climate (geophysical) variables. In the early stages, we have relied on NASA's instrument science teams in conjunction with an informal working group to provide scientific and technical expertise in making the selection. As Obs4MIPs has grown, the inclusion of new datasets or the replacement of existing datasets has required broader oversight. NASA has established an Obs4MIPs Science Working Group to help shepherd the process forward with PCMDI/DOE and NOAA participation.

Obs4MIPs is now being fostered by WCRP, and an international task team is being established by the WCRP's Data Advisory Council (WDAC) to help shepherd the evolution of obs4MIPs and provide a governance framework as it expands to more agencies and international contributors. In the meantime, we strongly encourage other observational teams and experts to consider contributing to Obs4MIPs. More information about Obs4MIPs and how to contribute data can be found at http://obs4mips.llnl.gov.

Along with the desire to have this activity serve as a means for observations to inform model development and evaluation, it is also hoped that it will lead to more feedback from the model development and research communities into the formulation of new observational systems.

ACKNOWLEDGMENTS. This research was partly carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Work at Lawrence Livermore National Laboratory was carried out under the auspices of the U.S. DOE under contract DE-AC52-07NA27344. Renu Joseph of DOE has been instrumental in helping to foster this interagency collaborative effort.

FOR FURTHER READING

Bodas-Salcedo, A., and Coauthors, 2011: COSP: Satellite simulation software for model assessment. *Bull. Amer. Meteor. Soc.*, **92**, 1023–1043, doi:10.1175/2011BAMS2856.1.

Gleckler, P., R. Ferraro, and D. Waliser, 2011: Improving use of satellite data in evaluating climate models. *Eos, Trans. Amer. Geophys. Union*, **92**, 172, doi:10.1029/2011EO200005.

IPCC, 2013: Summary for policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker et al., eds. Cambridge University Press, 3–29.

Jonkheid, B. J., R. A. Roebeling, and E. van Meijgaard, 2012: A fast SEVIRI simulator for quantifying retrieval uncertainties in the CM SAF cloud physical property algorithm. *Atmos. Chem. Phys.*, **12**, 10 957–10 969, doi:10.5194/acp-12-10957-2012.

Rienecker, M. M., and Coauthors, 2011: MERRA—NASA's Modern-Era Retrospective Analysis for Research and Applications. *J. Climate*, **24**, 3624–3648, doi:10.1175/JCLI-D-11-00015.1.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An Overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498, doi:10.1175/BAMS-D-11-00094.1.

Teixeira, J., D. Waliser, R. Ferraro, P. Gleckler, and G. Potter, 2011: Satellite observations for CMIP5 simulations. *CLIVAR Exchanges (Special Issue on the WCRP Coupled Model Intercomparison Project Phase 5—CMIP5)*, **16**, 46–47.

Williams, D. N., and Coauthors, 2009: The Earth System Grid: Enabling access to multimodel climate simulation data. *Bull. Amer. Meteor. Soc.*, **90**, 195–205, doi:10.1175/2008BAMS2459.1.

MPING

Crowd-Sourcing Weather Reports for Research

BY KIMBERLY L. ELMORE, Z. L. FLAMIG, V. LAKSHMANAN, B. T. KANEY, V. FARMER, HEATHER D. REEVES, AND LANS P. ROTHFUSZ

An app for smartphones allows citizen scientists to provide observations about winter precipitation type at the surface at least equivalent in quality to human-augmented Automated Surface Observing System (ASOS) observations.

WHY THIS IS SUCH A GREAT IDEA. Late in 2011 a planned upgrade of the Weather Service Radar-1988 Doppler (WSR-88D) radar network began in earnest (www.roc.noaa.gov/WSR88D/PublicDocs/DualPol/DPstatus.pdf). This upgrade adds vertical polarization information to the existing horizontal polarization information (Ryzhkov et al. 2005a). The overarching focus for the dual-polarization upgrade is improvement in quantitative precipitation estimation (QPE) and, in this, there has been some success (Cocks et al. 2012; Berkowitz et al. 2013), including data quality improvement (Ryzhkov et al. 2005a), discrimination of the rain/snow line using the ρ_{HV} field (Ryzhkov and Zrnic 1998), hail detection (Ryzhkov et al. 2005a), and tornado detection via the debris signature (Ryzhkov et al. 2005b). But, even beyond these successes, dual-polarization radar offers far more capabilities, especially when merged with environmental data.

Perhaps chief among the added benefits of polarimetric radar is the ability to help discriminate between different precipitation species or types in winter weather. Precipitation type information is useful for various reasons. For example, forecasters need knowledge of winter precipitation type because it helps inform them whether or not the thermodynamic profiles are developing as expected. Winter weather precipitation type affects surface transportation support and road maintenance since precipitation type affects decisions about whether to treat roads and, if treatment is needed, what process to use. Aviation ground deicing operations are heavily affected by precipitation type, but certain types of precipitation (e.g., ice pellets) also indicate freezing rain aloft and thus flight conditions that should be avoided. Electric utility infrastructure suffers during freezing precipitation events, which means that knowledge of where freezing precipitation is occurring helps utilities plan how best to maintain the power grid.

Within the suite of dual-polarization algorithms fielded with the upgraded radars is the hydrometeor classification algorithm (HCA; Park et al. 2009), which is used mostly for QPE enhancement (Giangrande and Ryzhkov 2008; Berkowitz et al. 2013). Because the HCA was developed with warm season convection in mind and because it assumes (among other things) a monotonic temperature profile with height and is

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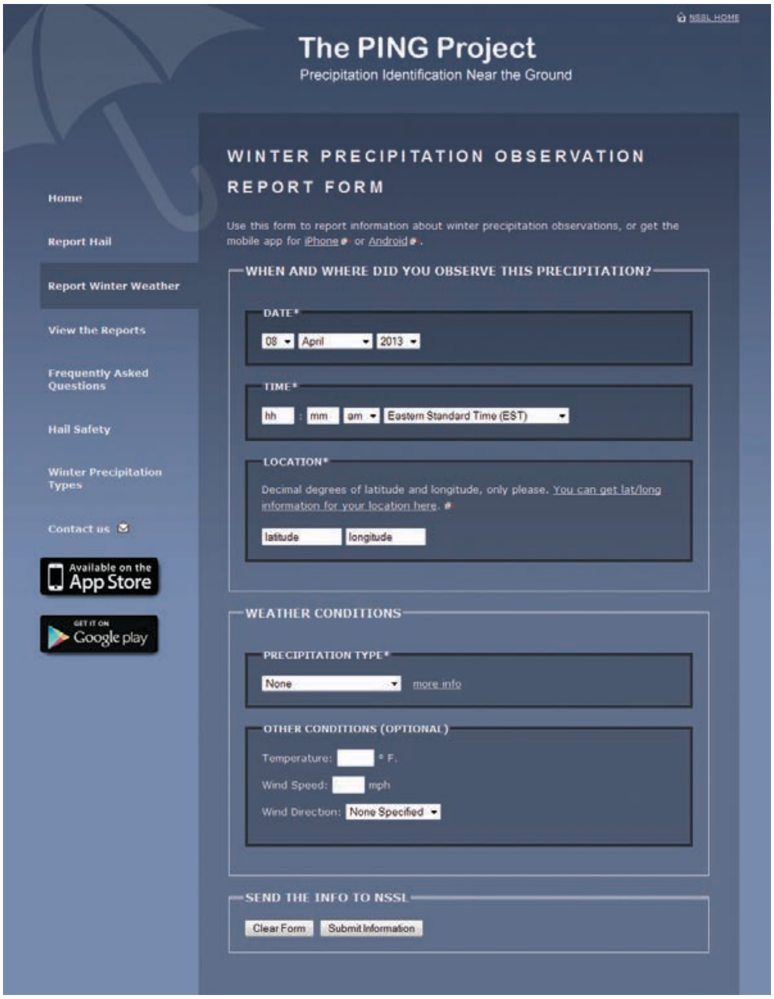

Fig. 1. The original web page interface used to enter mPING observations. Submissions had to include the observer's location in decimal latitude and longitude, as well as time and time zone. Precipitation type is selected via radio buttons.

fundamentally intended to provide hydrometeor type within the radar pulse volume (not at the surface), its performance is compromised in winter weather, especially in the presence of warm, elevated layers (Elmore 2011). Any failure in the monotonicity assumption for temperature with height is a significant issue with HCA in winter weather because the HCA depends upon the existence of only one freezing level through which precipitation falls. Within winter weather, this assumption is often invalid.

The inadequacy of the current HCA when misapplied to diagnose winter surface precipitation type has been noted by operational meteorologists within the NWS and the broadcast media, with the strong desire for improved surface HCA output expressed by both groups. To address the specific need for surface hydrometeor type information in winter weather, the winter surface hydrometeor classification algorithm (WSHCA) is being developed (Schuur et al. 2012). To both develop and also validate such algorithms and other dual-polarization algorithms, described in Ryzhkov et al. (2013) and Lakshmanan et al. (2014), high-quality surface observations of precipitation type are needed. The current automated observing systems do not provide information about some types, such as ice pellets. Yet, these types have important operational ramifications. Thus, a better source of precipitation type data is needed.

Observing precipitation requires no advanced education in meteorology and the general public can distinguish between rain and snow; different forms of frozen precipitation (e.g., snow versus ice pellets); and, within limits (discussed below), the difference between nonfreezing and freezing precipitation. Because such knowledge is common, it seems only natural to use it. The new generation of web-enabled portable devices ("smart" devices) offers an ideal platform for laypeople located almost anywhere to contribute their knowledge toward improving dual-polarization algorithms. To help laypeople identify different precipitation types, the mobile Precipitation Identification Near the Ground project (mPING) maintains a web page with descriptions of the various precipitation types (www.nssl.noaa.gov/projects/ping/types.php). Precipitation types are also internally documented within the app itself.

To employ these devices requires an application, or "app," that reports back only the required data. Meteorological citizen scientist projects are not new: the Community Collaborative Rain, Hail and Snow (CoCoRaHS) was introduced in 1995 (Cifelli et al. 2005). Other examples exist outside of meteorolog—for example, Project Budburst (http://budburst.org/). However, mPING is unusual, if not unique, in that participants are intentionally kept anonymous and so need not register and, in fact, cannot register because there is no registration process.

Among the requirements are that the observations must be compact—free-form comments and photographs of precipitation fail in this regard because of their sheer volume, but also because photographs, in particular, cause an enormous increase in required bandwidth. Another requirement is to use the device's intrinsic GPS location and time for tagging observations. Perhaps the final requirement is that the app should keep the reporter anonymous to ensure privacy.

ARCHITECTURE. The mobile Precipitation Identification Near the Ground project (now changed to meteorological Phenomena Identification Near the Ground in a recent upgrade to the app) originated in 2006 as a way to gather validation information to assess the performance of the HCA as a surface precipitation type classifier (Elmore 2011). In the project's initial form, observations were entered through a web page interface (Fig. 1). Observations were requested within a 150-km radius of the KOUN (Norman, Oklahoma) test bed radar because, at the time, it was the sole WSR-88D-based dual-pol prototype. Users provided their latitude and longitude, based on either their own knowledge or through any of a number of web-based geolocation services, the time of the observation, and, through radio buttons, the precipitation type. The resulting data were added to a large database system maintained at the National Severe Storms Laboratory (NSSL). While data collection through the web form continues, it has become clear that with the nationwide dual-pol upgrade to the WSR-88D, a more effective data gathering means is both needed and attainable.

This led to a program based on the Severe Hazards and Verification Experiment (SHAVE; Ortega et al. 2009) wherein students actively probe areas of winter weather via telephone calls, seeking observations of precipitation type. While the winter SHAVE was successful, it became clear that targeting areas of transitional precipitation types, such as mixes, freezing precipitation, and ice pellets, is not straightforward; standard surface observations are inadequate; radar clues are ambiguous; and such regions are relatively small and transient in nature.

One of us (Flamig) has substantial experience developing weather-based apps for iOS devices and offered to help develop one that would support widespread, easy submission of precipitation type observations. The iOS development of mPING and the Android version are functionally identical but follow different operating system guidelines and so look very different. So far, apps exist only for the iOS and Android platforms, as these make up about 80% of the devices currently in use. Versions for other platforms may be developed in the future.

Among the key features of mPING are immediate feedback to users that their submission has been accepted and the ability to display and even download all submissions using a web-based display (viewable from within the apps). Up to 24 h of reports from across the continental United States and for any day back to November 2006 can be displayed. While users remain anonymous, the report density and frequency is such that when the display is centered on the user's location and magnified (zoomed in), individual reports are easily seen when they appear. The display can be seen using a desktop browser at www.nssl.noaa.gov/projects/ping/display/ (Fig. 2). A simplified display (with zoom capability) is used for mobile devices (www.nssl.noaa.gov/projects/ping/display/phone.php).

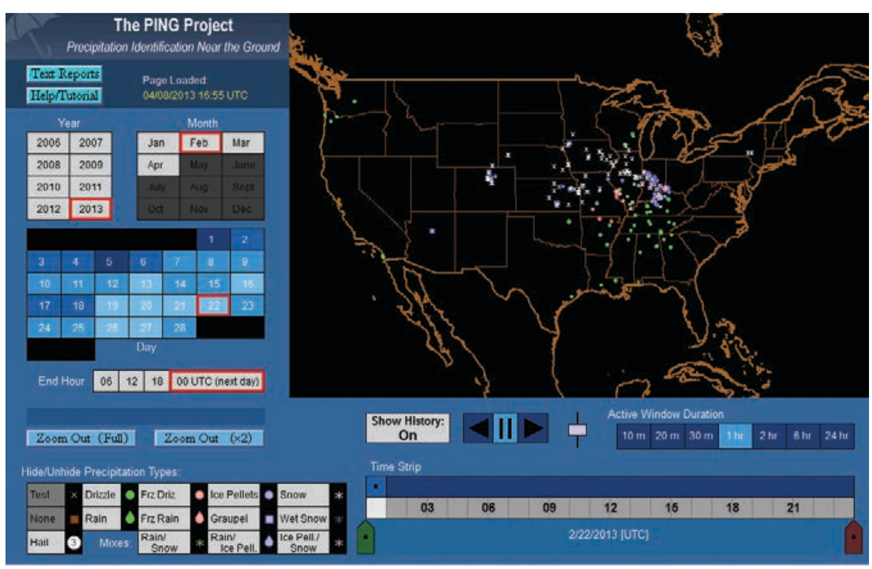

FIG. 2. Display of all observations submitted in a single hour spanning 0000–0100 UTC 22 Feb 2013. The display can loop over selected periods showing the spatiotemporal progression of precipitation and precipitation type. In addition, a rectangle can be created by a mouse click-and-drag operation such that any subregion can be zoomed and displayed. Text versions of reports, accurate to two decimal places, can be displayed in a new tab using the "text reports" button and saved with a cut-and-paste operation.

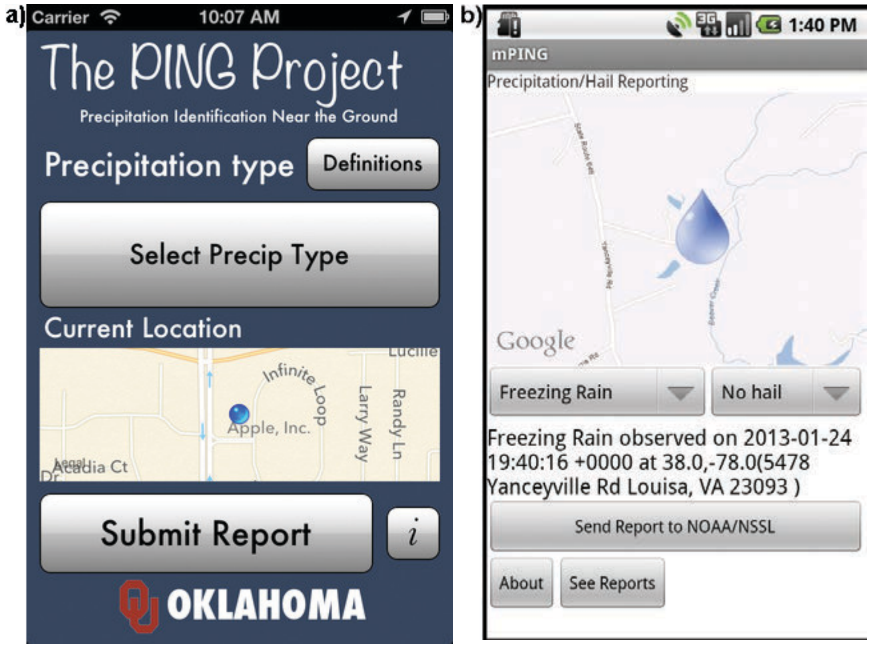

Fig. 3. The mPING interface is shown for (left) the iOS systems and (right) the Android systems. The interfaces are kept intentionally simple and relatively uncluttered.

CONSIDERATIONS. We paid particular attention to simplicity. The user interface had to be very simple (Fig. 3), and data entry had to also be simple and intuitive, not because users lack sophistication, but because the app must remain unobstrusive. Users are extremely concerned about battery life, so the app has to be smart about the way it uses the GPS engine, which is a significant power drain. To both avoid confusion and to standardize the various types that can be reported, users choose from a limited number of precipitation types with a pull-down menu (Fig. 4). These types are test, none, hail, rain, drizzle, freezing rain, freezing drizzle, snow, wet snow, mixed rain and snow, mixed rain and ice pellets, mixed ice pellets and snow, ice pellets/sleet, and graupel/snow grains. Descriptions of the various precipitation types are internally documented within the app itself and also described on the mPING website at www.nssl.noaa.gov/projects/ping/types.php. For hail only, an additional parameter (size to the nearest 0.6 cm or 0.25 in.) is also required. Location and observation time (in UTC) are gathered from the device's internal GPS engine. Thus, only the precipitation type is provided by the user; all else is automatic. The WSHCA research at NSSL is focused exclusively on precipitation type so no intensity estimates are requested.

To avoid rapid, inadvertent data submission while the device is being carried in a pocket or purse, a 5-min lockout timer is enforced so that observations can be entered at no higher frequency. The 5-min lockout timer also suppresses malicious attempts to rapidly enter misleading data. The most recent release

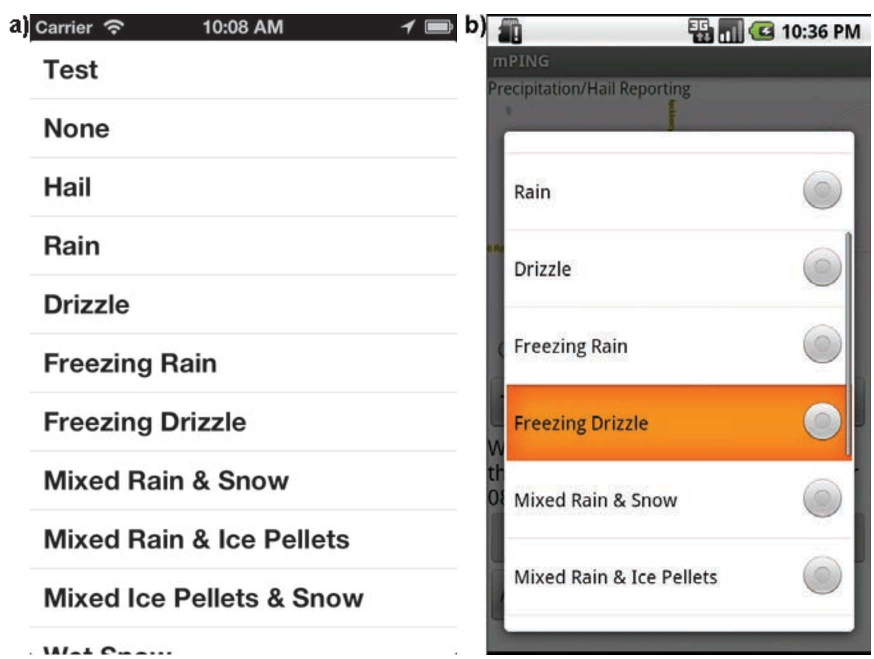

Fig. 4. Precipitation type choice is made via a drop-down list or menu. Users simply select the observed precipitation type, at which point the app returns to the submit page. Two taps (and possibly a swipe) of the screen are all that is needed to submit an observation once the app is opened. An extra tap is needed for hail because the user must select the (preferably measured) hail size using a slider bar.

of the app has relaxed the lockout timer to 30 s so that rapidly changing convective phenomena can be better captured.

Both the mobile apps and the web page submit information via HTTP to a common database that validates user input (to prevent malicious attacks, but not to quality control the observations) and provides persistent storage of the public reports. All quality control is done in postprocessing. We have so far found that these crowdsourced data are very high quality when measured by internal temporal and spatial consistency. It is clear to us that the vast majority of entries are made with the best intentions. Even so, mistakes occur and the occasional misleading report appears. Fortunately, misleading reports in particular are very obvious (e.g., 20-cm hail reports in the absence of convection, rain in midst of large-scale snow, reports of precipitation in areas known to be clear, etc.) and are easy to remove by hand through simple inspection.

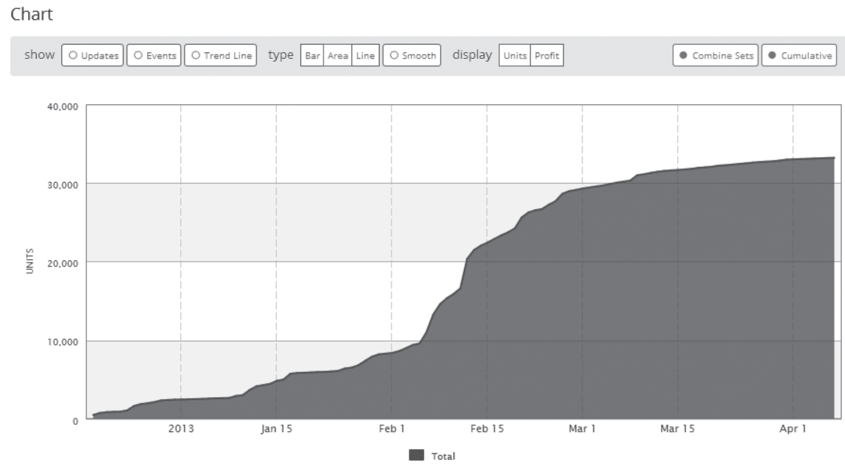

Fig. 5. Download history for the combined iPhone and Android mPING versions. Increases in download rates are typically the result of media attention. In particular, the increased download rates spanning 6–13 Feb 2013 are due to the National Oceanic and Atmospheric Administration (NOAA) press release followed on 12 Feb 2013 by a brief feature on the National Public Radio *All Things Considered* newscast.

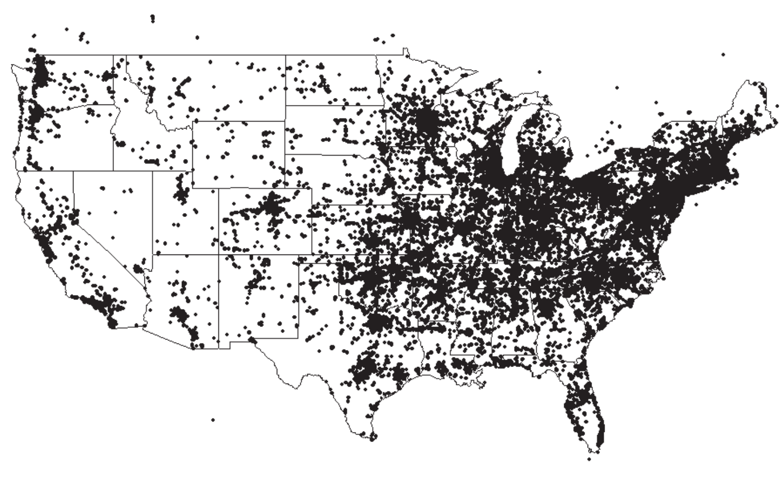

Fig. 6. Spatial distribution of the 208,791 mPING observations submitted between 19 Dec 2012 and 23 April 2013. Because of population distribution, coverage over the eastern half of the continental United States (CONUS) is much better than the western half. Reports that appear outside of the CONUS are legitimate.

WHAT WE HAVE LEARNED AND WHERE WE MAY GO NEXT.

We have become convinced that immediate feedback to the user is very important and figures largely in the success of the mPING app. Not only are users rewarded by seeing that their data are actually being ingested, but they report an overall increased interest in weather and the project by simply watching the reports as they come in and change with time. In addition, the data are open and publicly available for text download in 24-h increments via the main display web page.

When these apps were initially released, the announcement was limited to only social media (i.e., Facebook, Twitter, etc.). The formal press release occurred much later, on 6 February 2013. Yet, we found that once mention was made within social networks, word spread rapidly about both the apps and the mPING project among those who are interested in weather but are not necessarily professional meteorologists; evidence is apparent in the download history of both the iOS and Android versions of the app (Fig. 5) and in the ~209,000 reports received between 19 December 2012 and 23 April 2013 (Fig. 6; Table 1). During this time, we have occasionally seen areas around cities become very active within the span of about an hour following mention of the app and project, often in cooperation with a local National Weather

Table 1. Breakdown by type of the 208,791 mPING reports received starting 19 Dec 2012 and ending 23 April 2013.

Type	Number
Test	13,188
None	45,348
Rain	38,713
Drizzle	17,485
Freezing rain	3,234
Freezing drizzle	1,909
Snow	50,470
Wet snow	13,474
Ice pellets	5,574
Graupel	4,091
Rain and snow mixed	6,533
Rain and ice pellets mixed	4,644
Snow and ice pellets mixed	4,123

Service Forecast Office. Even before the formal media announcement, several media articles were published about mPING as well as at least one favorable editorial (e.g., http://idealab.talkingpointsmemo.com/2013/02/mping-noaa-storm-app.php, www.npr.org/blogs/alltechconsidered/2013/02/25/171715999/this-app-uses-the-power-of-you-to-report-the-weather, and www.bostonglobe.com/editorials/2013/02/08/the-folks-behind-national-weather-service-are-now-crowdsourcing-nemo/5MD65k88EfDUA30iV8DY3K/story.html).

Among the informal comments made on various social networks and in e-mails to the authors, users find two favorable characteristics that stand out. In no particular order, the first is the simplicity of the interface. Users appreciate how easy mPING is to use and how quickly they can enter observations and then be about their business. The second is immediate, uncluttered feedback, which both satisfies users' basic curiosity and helps retain their interest, even when winter weather is not occurring in their immediate vicinity. Both of these characteristics, taken together, may constitute a fundamental dual requirement for future efforts like mPING. The simple observation entry interface avoids tedium and immediate feedback keeps users' interest.

We suspect that allowing users to submit a "test" report and then see the report appear on the real-time display satisfies a reasonable desire to use and test the app immediately upon installation. Test report submission also strengthens users' confidence that the app does what is claimed. While we have no proof, we also suspect that the ability to submit test reports helps users resist the temptation to falsely report precipitation to test the app and see a report when no precipitation is occurring.

Even though the vast majority of observers are not trained in meteorological observations, we find that the observations appear to be of remarkably consistent and of high quality. In several instances, one of us (Reeves) polled professors of meteorology in regions experiencing complex winter precipitation, such as ice pellets, freezing precipitation, or mixed precipitation. In every case, these trained meteorologists validate the reports that are nearest to them in both time and space.

Transitional precipitation types that can be reported by Automated Surface Observing System (ASOS) stations are freezing rain and, when augmented by a human observer, ice pellets. These are among the most variable winter precipitation types in both space and time owing to the complex thermodynamic profiles required to generate them (Baldwin and Contorno 1993; Bourgouin 2000; Czys et al. 1996; Ramer 1993). To help quantitatively assess the reliability of mPING observations within these transitional precipitation types, observations of ice pellets and freezing rain are compared to manually augmented surface observations made by trained observers at the sites shown in Fig. 7. Only explicit mPING observations of ice pellets and freezing rain between 1 December 2012 and 31 March 2013 are used in this comparison; all other categories, including graupel and freezing drizzle, are excluded. This yields a total of 2382 observations by trained observers that can be matched to mPING reports. A comparison of trained observations to mPING observations is provided in Fig. 8. In this figure, both the length of time and the distance between the trained observation and surrounding mPING observations are varied. For freezing rain, as the amount of time between the mPING observation and

Fig. 7. Locations of human-augmented ASOS stations used to assess reliability of mPING reports.

the trained observation is decreased, the percent of mPING observations that agree with a given trained observation increases (Fig. 8a). Those mPING observations that are within about 5 km and 12 min of a trained observation have rates of agreement in excess of 80%. The picture is somewhat different for ice pellet (PL) observations (Fig. 8b). Here, the rate of agreement is maximized (at 70%) for distances between 15 and 30 km. For this precipitation type, the sampling of PL observations is comparatively limited (761) and there are relatively few mPING observations that are within 15 km of trained observations. Nevertheless, these rates of agreement are rather good, given that these forms of precipitation often occur in narrow zones or in mixes with other forms (Crawford and Stewart 1995; Robbins and Cortinas 2002; Cortinas et al. 2004) and suggest that most of the time the untrained observers participating in the mPING program are providing high-quality observations.

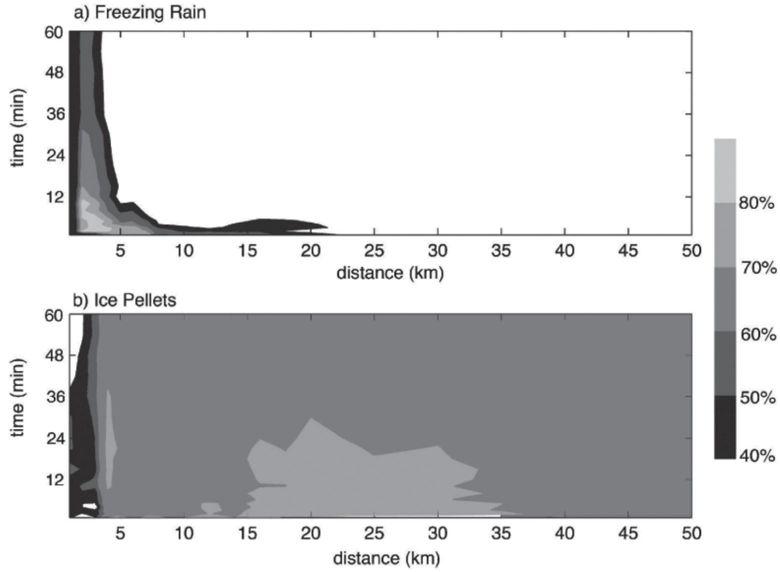

Fig. 8. Depiction of agreement between human-augmented ASOS and mPING observations. Grayscale shading shows percentage agreement, vertical axis time separation of mPING report following the augmented ASOS observation time, and horizontal axis is distance from ASOS station in kilometers.

Even in the face of this evidence, mPING observation quality has limits. Based on real-time intercomparisons between mPING observations and comparisons to human-augmented ASOS observations, we have limited confidence that most people can distinguish between ice pellets and graupel, or that all observers use the same definition for "wet snow"; thus, the latest versions of the app no longer support these precipitation types. However, we have relatively high confidence that people properly identify mixes. While the version of the app used in this work contains 13 different precipitation types and all of the categories are always retained, for purposes of developing the WSHCA classifier and for comparing forecast precipitation type to mPING observations (Baldwin and Contorno 1993; Bourgouin 2000; Czys et al. 1996; Ramer 1993), these 13 categories are collapsed to only four: snow, rain, freezing rain, and ice pellets full in the understanding that these four "collapsed" types do not imply homogeneous precipitation type, but rather are in the spirit of major components. These four types are also the primary precipitation types developed by the various precipitation type algorithms used in numerical model post processing. Early work intercomparing mPING report self-consistency (not shown) indicates that the most consistent results are created when mixes with a rain component are collapsed to the nonrain component; that is, rain/snow mixes are collapsed to snow. Similarly, snow/ice pellet mixes appear most consistent when collapsed to ice pellets. These methodologies remain a topic of continuing research.

These data are potentially invaluable for the development of precipitation type algorithms that work with the upgraded dual-polarization WSR-88D radars and also for hail-size algorithms planned for the WSR-88D dual-pol radars. These data may also prove useful for additional studies and works, including (but not limited to) precipitation type algorithms for numerical models, ground icing for road maintenance and aviation operations, and even aviation in-flight icing work.

The app itself is not static: enhancements have already been made and additional mobile platforms may be considered in the future. New categories will be added, some will be dropped, and some categories that describe meteorological affects (such as flooding) and nonprecipitating weather (such as storm damage and obstructions to visibility) will be added. Plans are in motion to add resulting data stream as an Advanced Weather Interactive Processing System (AWIPS) data feed.

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REFERENCES

Baldwin, E. B., and S. P. Contorno, 1993: Development of a weather-type prediction system for NMC's mesoscale ETA model. Preprints, *13th Conf. on Weather Analysis and Forecasting,* Vienna, VA, Amer. Meteor. Soc., 86–87.

Berkowitz, D. S., J. A. Schultz, S. Vasiloff, K. L. Elmore, C. D. Payne, and J. B. Boettcher, 2013: Status of dual pol QPE in the WSR-88D network. Preprints, *27th Conf. on Hydrology,* Austin, TX, Amer. Meteor. Soc., 2.2. [Available online at https://ams.confex.com/ams/93Annual/webprogram/Paper221525.html.]

Bourgouin, P., 2000: A method to determine precipitation types. *Wea. Forecasting,* **15,** 583–592, doi:10.1175/1520-0434(2000)0152.0.CO;2.

Cifelli, R., N. Doesken, P. Kennedy, L. D. Carey, S. A. Rutledge, C. Gimmestad, and T. Depue, 2005: The Community Collaborative Rain, Hail, and Snow Network: Informal education for scientists and citizens. *Bull. Amer. Meteor. Soc.,* **86,** 1069–1077, doi:10.1175/BAMS-86-8-1069.

Cocks, S. B., D. S. Berkowitz, R. Murnan, J. A. Schultz, S. Castleberry, K. Howard, K. L. Elmore, and S. Vasiloff, 2012: Initial assessment of the dual-polarization quantitative precipitation estimate algorithm's performance for two dual-polarization WSR-88Ds. Preprints, *28th Conf. on Interactive Information Processing Systems (IIPS),* New Orleans, LA, Amer. Meteor. Soc., 15 pp. [Available online at https://ams.confex.com/ams/92Annual/webprogram/Paper203568.html.]

Cortinas, J. V., Jr., B. C. Bernstein, C. C. Robbins, and J. W. Strapp, 2004: An analysis of freezing rain, freezing drizzle, and ice pellets across the United States and Canada: 1976–1990. *Wea. Forecasting,* **19,** 377–390, doi:10.1175/1520-0434(2004)0192.0.CO;2.

Crawford, R. W., and R. E. Stewart, 1995: Precipitation type characteristics at the surface in winter storms. *Cold Reg. Sci. Technol.,* **23,** 215–229, doi:10.1016/0165-232X(94)00014-O.

Czys, R. R., R. W. Scott, K. C. Tang, R. W. Przybylinski, and M. E. Sabones, 1996: A physically based, nondimensional parameter for discriminating between locations of freezing rain and ice pellets. *Wea. Forecasting,* **11,** 591–598, doi:10.1175/1520-0434(1996)0112.0.CO;2.

Elmore, K. L., 2011: The NSSL hydrometeor classification algorithm in winter surface precipitation: Evaluation and future development. *Wea. Forecasting,* **26,** 756–765, doi:10.1175/WAF-D-10-05011.1.

Giangrande, S. E., and A. V. Ryzhkov, 2008: Estimation of rainfall based on the results of polarimetric echo classification. *J. Appl. Meteor.,* **47,** 2445–2462, doi:10.1175/2008JAMC1753.1.

Lakshmanan, V., C. Karstens, J. Krause, and L. Tang, 2014: Quality control of weather radar data using polarimetric variables. *J. Atmos. Oceanic Technol.,* **31,** 1234–1249, doi:10.1175/JTECH-D-13-00073.1.

Ortega, K. L., T. M. Smith, K. L. Manross, K. A. Scharfenberg, A. Witt, A. G. Kolodziej, and J. J. Gorley, 2009: The severe hazards analysis and verification experiment. *Bull. Amer. Meteor. Soc.,* **90,** 1519–1530, doi:10.1175/2009BAMS2815.1.

Park, H.-S., A. V. Ruzhkov, D. S. Zrnić, and K.-E. Kim, 2009: The hydrometeor classification algorithm for the polarimetric WSR-88D: Description of application to an MCS. *Wea. Forecasting,* **24,** 730–748, doi:10.1175/2008WAF2222205.1.

Ramer, J., 1993: An empirical technique for diagnosing precipitation type from model output. Preprints, *Fifth Int. Conf. on Aviation Weather Systems,* Vienna, VA, Amer. Meteor. Soc., 227–230.

Robbins, C. C., and J. V. Cortinas Jr., 2002: Local and synoptic environments associated with freezing rain in the contiguous United States. *Wea. Forecasting,* **17,** 47–65, doi:10.1175/1520-0434(2002)0172.0.CO;2.

Ryzhkov, A. V., and D. S. Zrnic, 1998: Discrimination between rain and snow with a polarimetric radar. *J. Appl. Meteor.,* **37,** 1228–1240, doi:10.1175/1520-0450(1998)0372.0.CO;2.

——, T. J. Schuur, D. W. Burgess, P. L. Heinselman, S. E. Giangrande, and D. S. Zrnic, 2005a: The joint polarization experiment: Polarimetric rainfall measurements and hydrometeor classification. *Bull. Amer. Meteor. Soc.,* **86,** 809–824, doi:10.1175/BAMS-86-6-809.

——, ——, ——, and D. S. Zrnic, 2005b: Polarimetric tornado detection. *J. Appl. Meteor.,* **44,** 557–570, doi:10.1175/JAM2235.1.

——, M. R. Kumjian, S. Ganson, and P. Zhang, 2013: Polarimetric radar characteristics of melting hail. Part II: Practical implications. *J. Appl. Meteor. Climatol.,* **52,** 2871–2886.

Schuur, T. J., H.-S. Park, A. V. Ryzhkov, and H. D. Reeves, 2012: Classification of precipitation types during transitional Winter weather using the RUC model and polarimetric radar retrievals. *J. Appl. Meteor. Climatol.,* **51,** 763–779.

SURFACE PRESSURE OBSERVATIONS FROM SMARTPHONES

A Potential Revolution for High-Resolution Weather Prediction?

BY CLIFFORD F. MASS AND LUKE E. MADAUS

Pressure observations from smartphones have the potential to provide millions of observations per hour that could revolutionize high-resolution weather prediction.

During the past few years, tens of millions of smartphones with relatively accurate pressure sensors have been sold throughout the world, with the goal of providing information for internal navigation within buildings and better altimetry, among other uses. A smartphone is defined here as a mobile phone with substantial computational ability, a high-resolution screen, and wifi and GPS capabilities, in addition to the phone and text capabilities of standard cellular phones. Smartphones are capable of running a wide variety of applications (apps) and are available with a number of operating systems (e.g., Apple iOS, Google Android, Windows mobile). By 2016, industry sources (IHS Technology; https://technology.ihs.com/) expect that between 500 million and one billion smartphones and tablets will have the capacity to measure pressure as well as parameters such as position, humidity, and temperature. Ultra-dense networks of pressure observations provided by smartphones and other portable platforms could contribute detailed information describing mesoscale phenomena such as convective cold pools, mountain waves, fronts, and others. This paper will examine the potential of such massive numbers of surface observations to greatly improve our ability to describe and forecast the three-dimensional structure at the atmosphere, potentially leading to revolutionary improvements in high-resolution numerical weather prediction.

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WHY IS SURFACE PRESSURE SO SPECIAL?

Pressure is perhaps the most valuable surface meteorological variable observed regularly. Unlike surface air temperature and humidity, surface pressure reflects the deep structure of the overlying atmosphere. Surface pressure has fewer of the observational problems that plague surface wind, temperature, and humidity; unlike wind and temperature, pressure can be measured inside or outside of a building, in or out of the shade, and is not seriously impacted by nearby obstacles or urbanization. Surface pressure is not influenced by the characteristics of the underlying surface, as are temperature and wind. Although surface pressure measurements can have systematic biases like other surface variables, pressure biases for a static sensor are generally unchanging (perhaps owing to poor elevation information or calibration) and thus can be easily removed by straightforward quality control algorithms.

Several recent studies, most using ensemble-based data assimilation systems, have demonstrated that surface pressure provides considerable information about three-dimensional atmospheric structures. Ensemble-based data assimilation systems are particularly adept in getting maximum value from surface pressure information; such systems produce flow-dependent background error covariances, build covariances based on the natural atmospheric structures in the model, and allow impacts for pressure on all other model variables throughout the atmospheric volume. On the synoptic scale, Whitaker et al. (2004) showed that a limited number of global surface pressure observations could produce a highly realistic twentieth-century reanalysis that closely resembled the analysis produced by the full collection of observing assets during a comparison period encompassing the later part of the century. Using regional assimilation of pressure observations from airport locations, Dirren et al. (2007) was able to reproduce synoptic-scale upper-air patterns over western North America and the eastern Pacific.

Although less work has been completed on the assimilation of surface pressure observations on the mesoscale, early investigations have been promising. Wheatley and Stensrud (2010) investigated the impacts of assimilating both surface pressure and 1-h pressure change for two convective events over the U.S. Midwest. Using a relatively coarse model resolution (30 km) and only assimilating airport Automated Surface Observing System (ASOS) observations, they found that surface pressure observations facilitated accurate depictions of the mesoscale pressure patterns associated with convective systems. More recently, Madaus et al. (2014) found that ensemble-based data assimilation of dense pressure observations can produce improved high-resolution (4 km) analyses and short-term forecasts that better resolve features such as fronts and convection. Considering the apparent promise of surface pressure observations for improving analyses and forecasts, the next step is to evaluate this potential by applying state-of-the-art data assimilation approaches to a pressure observation network encompassing conventional observations and enhanced with pressure data available from new observing platforms such as smartphones.

INCREASING AVAILABILITY OF FIXED SURFACE PRESSURE OBSERVATIONS. During the past decades, there has been an explosion in the availability of surface pressure observations across the United States. A quarter century ago, surface pressure observations were limited to approximately 1000 airport locations across the country. Today, these ASOS sites are joined by hundreds of networks run by utilities, air quality agencies, departments of transportation and others, plus public volunteer networks such as the Weather Underground (www.wunderground.com/) and the Citizen Weather Observer Program (CWOP; http://wxqa.com/). By combining these networks, tens of thousands of surface pressure observations are collected each hour across the United States. Over the Pacific Northwest region, encompassing mainly Washington, Oregon, and Idaho, roughly, 1800 pressure observations are currently collected each hour from approximately 70 networks (Fig. 1), compared to approximately 100 ASOS locations. As shown in that figure, even when large numbers of networks are combined, substantial areas, particularly in rural locations, have few pressure observations, and many observation locations only report once an hour. Fortunately, an approach for increasing radically the number and temporal frequency of surface pressure observations exists: the use of pressures from smartphones and other portable digital devices.

SMARTPHONE PRESSURE OBSERVATIONS. During the past two years a number of smartphone vendors have added pressure sensors,

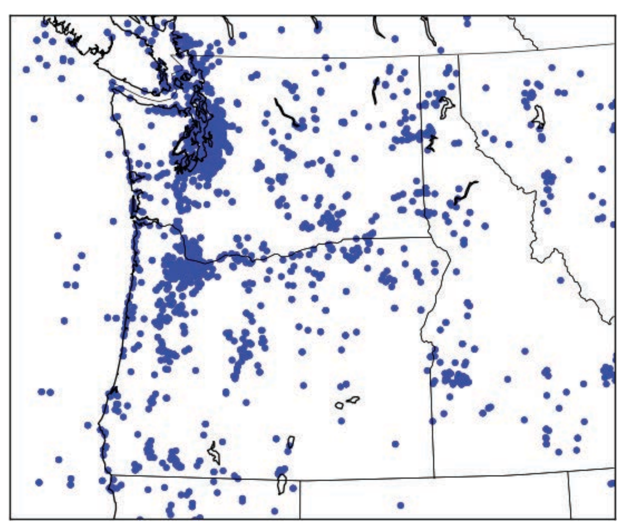

Fig. 1. Surface pressure locations for a typical contemporary period (from 0000 UTC 10 Nov to 2100 UTC 10 Dec 2012) from roughly 70 networks over the Pacific Northwest. Figure from Madaus et al. (2014).

predominantly to Android-based phones and tablets/pads. The main reason for installing these pressure sensors was to identify the floor on which the device is located or to aid in vertical altimetry. Samsung began using pressure sensors in its popular Galaxy S III smartphone in 2012 and such sensors have remained in the Galaxy S IV released in 2013 (Fig. 2) and the Galaxy S V (2014). Pressure sensors are also available in other Android phones and pads, including the Galaxy Nexus 4 and 10, Galaxy Note, Xoom, RAZR MAXX HD, Xiaomi MI-2, and Droid Ultra. According to industry analyst IHS Electronics and Media (https://technology.ihs.com/), approximately 80 million pressure-capable Android devices were sold in 2012, with expectations of 160 and 325 million units for 2013 and 2014, respectively. By 2015, IHS estimates that well over a half-billion portable devices worldwide will have the capability for real-time pressure observation, including over 200 million in North America. There is the strong expectation that non-Android device vendors such as Apple will include pressure sensors in upcoming smartphones and tablets. Thus, the potential may exist to increase the number of hourly pressure observations over the United States by roughly 10,000 times over the current availability from current networks.

Some insight into the potential availability and distribution of smartphone pressures is available from a map of the current U.S. coverage for the largest American cell phone network, Verizon (Fig. 3). Nearly all of the eastern two-thirds of the lower 48 states is covered, encompassing nearly the entire range of U.S. severe convective storms. Coverage over the western United States has gaps over the highest terrain and sparely populated desert areas, but is still extensive (covering perhaps 65% of the land area) and includes all the major West Coast population centers from Seattle to San Diego. Coverage over the Interstate Highway System is particularly good, even over less populated rural areas. The number of smartphone observations will undoubtedly be dependent on population density, with the largest over the eastern United States and the West Coast.

Fig. 2. The Samsung Galaxy S4 is one of several Android phones with high-quality pressure sensors. (Source: www.imgreview.info/samsung-galaxy-s4-active-orange/)

The accuracy and resolution of the pressure sensors in smartphones and tablets are surprisingly good. Many of the current Android devices use the ST Microelectronics LPS331 MEMS pressure sensor, which has a relative accuracy of ±0.2 hPa, an absolute accuracy of ±2.6 hPa, and includes temperature compensation (details at www.st.com/st-web-ui/static/active/en/resource/technical/document/datasheet/DM00036196.pdf). Such relative accuracy allows accurate determination of pressure change, the use of which is discussed later in this paper.

The potential for large numbers of smartphone pressure observations has attracted several application developers that have created Android apps that collect smartphone pressures and positions (through GPS or cell tower triangulation). One firm, Cumulonimbus, has developed the pressureNet app for Android phones and tablets (www.cumulonimbus.ca/). Smartphone owners must download the pressureNet app to allow their pressures to be reported; however, with the insertion of the pressureNet code into popular apps, it is expected that the number of smartphone pressures collected by Cumulonimbus will increase by one or two orders of magnitude during the next year. Currently, they are collecting tens of thousands of surface pressure observations globally each hour

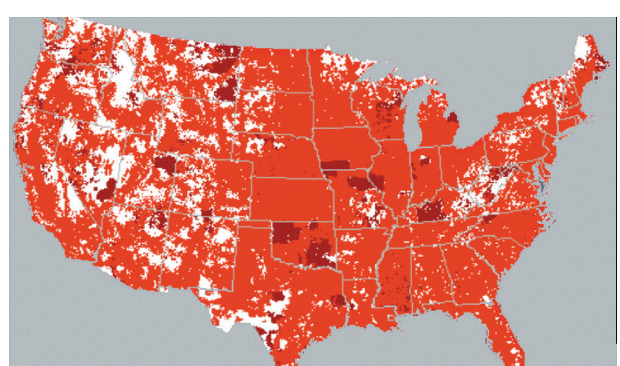

Fig. 3. Verizon cell phone coverage map on 4 Oct 2013. Darker red areas indicate enhanced digital coverage. White areas are without coverage.

and have made them available to the research community and others. Another group collecting pressure observations on Android phones is OpenSignal (http://opensignal.com/), whose application of the same name collects smartphone pressure observations, other meteorological parameters (temperature, humidity, and light levels), and wifi/cell phone signal levels. They have also developed an app, called WeatherSignal, that displays the meteorological observations provided by a phone. A plot of the pressureNet and OpenSignal observations at one time (0100 UTC 18 July 2014) over the U.S. and adjacent areas of Canada and Mexico is shown in Fig. 4. Although only about 100,000 hourly smartphone pressure observations are available today (July 2014) across the United States through the pressureNet app and OpenSignal apps, a small number compared to the millions of phones with pressure capabilities, there are still regions, such as the Northeast United States, with substantial smartphone observation densities that greatly enhance current observation networks.

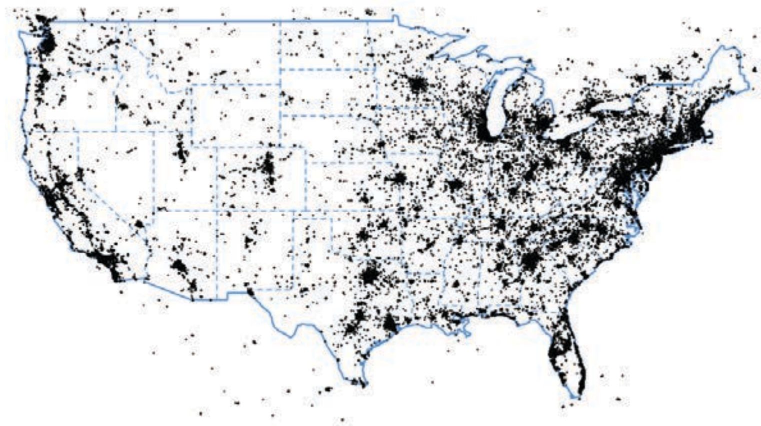

Fig. 4. Smartphone pressure observations for the hour ending 0100 UTC 18 Jul 2014. A total of 102,191 pressure observations were available at this time. Data are provided by two commercial firms: Cumulonimbus and OpenSignal.

Motor vehicles offer another potential platform for acquiring high-density pressure observations. Solid-state atmospheric pressure sensors are found in most cars and trucks, which also possess ambient temperature sensors for use in engine management computers (Mahoney and O'Sullivan 2013). The main challenges for use of vehicle pressure observations are position determination (easily dealt with by GPS), real-time communication, and privacy issues. A number of auto industry analysts (e.g., https://m2m.telefonica.com/m2m-media/m2m-downloads/detail/doc_details/530-connected-car-report-2013#530-Connected%20Car%20Report%202013-english) predict that most cars will have Internet connectivity by 2020.

OTHER SMARTPHONE WEATHER OBSERVING CAPABILITIES. Some smartphones, such as the Samsung Galaxy IV, have the capability to measure other environmental parameters such a battery temperature, humidity, magnetic field, and lighting intensity. Temperature and humidity measurements from smartphones are of far less value than pressure, since the dominant influence of the immediate environment (inside of a pocket or a building) produces readings that are unrepresentative of the conditions in the free air. However, a recent study found that with statistical training and correction using observed temperatures, large numbers of smartphone temperatures can be calibrated to provide useful measures of daily average air temperatures over major cities (Overeem et al. 2013b). Related work has shown that the attenuation of the microwave signals between cell towers is sensitive to precipitation intensity and that such information can be used to create precipitation maps that closely resemble radar reflectivitiy (Overeem et al. 2013a).

CHALLENGES IN USING SMARTPHONE PRESSURE OBSERVATIONS. The value of smartphone pressures in support of numerical weather prediction can be greatly enhanced with proper calibration, preprocessing, and preselection. Gross range checks can reject clearly erroneous pressures. Either pressure or pressure change can be assimilated by modern data assimilation systems. For pressure-change assimilation, only smartphones that are not moving should be used—something that can be determined from the GPS position and observed pressures from the phones (vertical movement will generally produce far more rapid pressure variations than meteorological changes).

The elevation of the smartphone is required to assimilate either pressure or pressure change. GPS elevations are available, but can have modest errors (typically ±10 m, roughly equivalent to a 1-hPa pressure error, the typical error variance used in most operational data assimilation systems; see http://gpsinformation.net/main/altitude.htm for a discussion on the vertical errors in GPS-based elevation). If one has a collection of pressures in an area, it might be reasonable to assume that the highest pressures reflect values on the first floor of residences or in a vehicle, representing pressure at roughly 1 m above ground elevation. Since it makes little sense to assimilate pressure observations in regions where models lack sufficient resolution to duplicate observed pressure features, pressure observations in such areas should be rejected when model and actual terrain are substantially different (Madaus et al. 2014). Clearly, some experimentation will be required for developing algorithms that derive maximum value from smartphone pressures.

WHAT KIND OF WEATHER FORECASTS COULD SMARTPHONE PRESSURES HELP THE MOST? Although an ultra-dense network of smartphone pressure observations would undoubtedly positively impact general weather prediction, there are several phenomena for which they might be particularly useful. One major problem is forecasting the initiation of severe convection, with models being initialized *before* any precipitation or radar echo is apparent. At such an early stage of development, subtle troughs, drylines, convergence lines, and remnants of past cold pools can supply major clues about potential convective development—information that dense collections of smartphone pressures might well be able to provide. The example in the next section of this paper illustrates the value of even a modest density of smartphone pressures for simulating a strong convective event. Forecasting the positions of fronts and major troughs, even a few hours in advance, can have large value for wind energy prediction since such features often are associated with sudden rapid ramp ups and ramp downs in wind energy generation. As shown by Madaus et al. (2014) the assimilation of dense pressure observations can shift fronts in a realistic way that substantially improves short-term wind forecasts. High-resolution pressure observations from smartphones might also aid in the initialization and monitoring of mesoscale troughing associated with downslope winds and leeside convergence zones. Dense pressure observations along coastlines could provide significant information regarding approaching weather features, including the positions of offshore low centers and fronts.

Even the densest portions of the U.S. surface observation network are generally too coarse to observe and initialize features on the meso-gamma (2–20 km) and smaller scales. Smartphone pressure observations may offer sufficient data to do so, particularly over the smartphone-rich regions of the eastern United States and West Coast. An interesting advantage of smartphone pressure observations is that they could be easily added in any location where power and cell phone coverage is available.

AN EXAMPLE OF ASSIMILATING SMARTPHONE PRESSURES. Although the smartphone pressure acquisition is still at an early stage, with observation densities orders of magnitude less than what will be available in a few years, it is of interest to try some initial assimilation experiments to judge the impacts of even modest numbers of smartphone pressures. To complete such a test, smartphone observations made available by Cumulonimbus's PressureNet app (PNET) were used to simulate an active convective event over the eastern slopes of the Washington Cascades that brought heavy showers and several lightning-initiated wildfires. For this experiment, an ensemble Kalman filter (EnKF) data assimilation system, adapted from one provided by the University Corporation for Atmospheric Research (UCAR) Data Assimilation and Research Testbed (DART) program (Anderson et al., 2009), was applied at 4-km grid spacing and used the Weather Research and Forecasting (WRF) model, V3.1. The ensembles (64 members) for these experiments were cycled every 3 h from 1200 UTC 29 June through 1200 UTC 30 June 2013. The impacts of smartphone pressures were examined for a 3-h period ending on 0300 UTC 30 June 2013. During that period there were 110 aviation routine weather report (METAR) observation sites and 350 smartphone pressure locations available.

Figure 5 shows both the surface pressures provided by the conventional ASOS network (METAR, blue

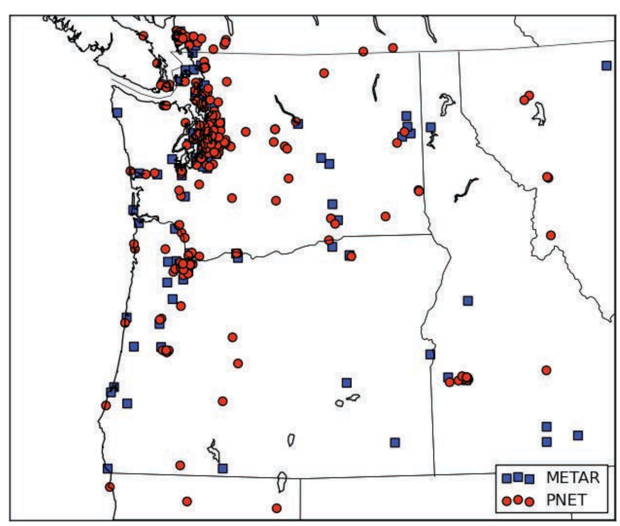

Fig. 5. Smartphone pressure observations (PNET) and pressure measurement sites from ASOS observation locations (METAR) at 0000 UTC 30 Jun 2013.

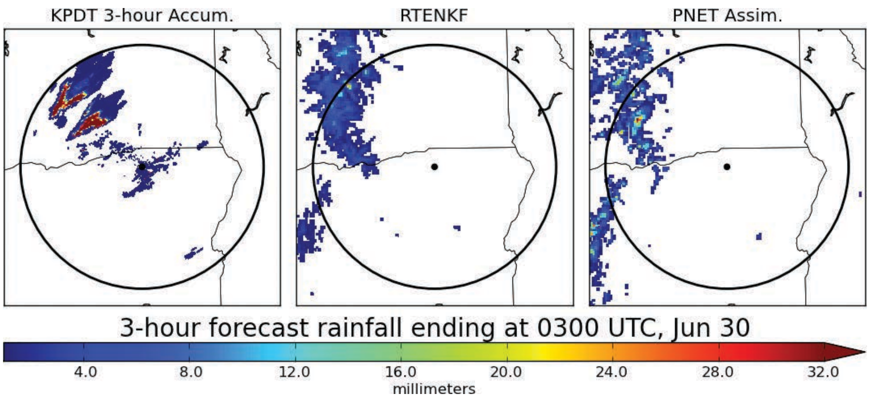

Fig. 6. 3-h precipitation from the Pendleton (PDT) radar, as well as ensemble means from the University of Washington real-time ensemble Kalman filter system (RTENKF) and the same system using pressures from smartphones, for a 3-h period ending at 0000 UTC 30 Jun 2013.

squares) and the smartphone pressures (PNET, red dots) available at 0000 UTC 30 June 2013. A number of smartphone pressures were available over the eastern slopes of the Cascades, the region of strongest convection. The accumulated rainfall estimated using the Pendleton, Oregon, National Weather Service radar (PDT) for the 3 h ending at 0300 UTC 30 June (Fig. 6) shows substantial accumulation (up to approximately 32 mm) from intense convective cells. The University of Washington runs a real-time ensemble Kalman filter data assimilation system (RTENKF) that uses conventional surface observations, radiosondes, Aircraft Communications Addressing and Reporting System (ACARS) observations, and satellite-based cloud/water vapor track winds (Torn and Hakim 2008). This system, run on a 3-h update cycle, produced 3-h precipitation totals shown in Fig. 6. This modeling system did produce some convective showers over and to the east of the Cascades, but failed to duplicate the intensity of the leeside showers and had considerable spread in convective locations. Figure 6 shows the result of adding the smartphone pressure observations (Fig. 5) to the mix of observations used in the RTENKF system. With the added pressure observations, the ensemble system produced far more intense convective cells east of the Cascade crest, with some with orientations and magnitudes more reminiscent of the observed than provided by the RTENKF system. In addition, more ensemble members were near the observed location of the most intense convection (Fig. 7). This, of course, represents only one case, but suggests that assimilating smartphone pressures can both change and enhance short-term mesoscale forecasts. It is reasonable to expect that further increases in the number of pressure observations would provide additional improvements in convective and other forecasts.

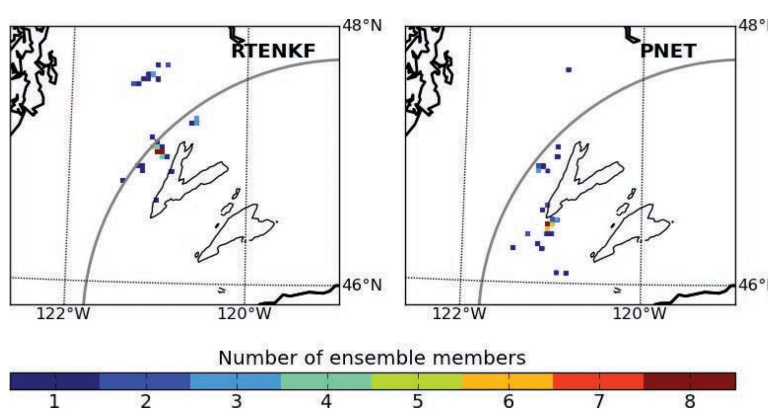

Fig. 7. The number of ensemble members with a local maxima in 3-h precipitation of at least 20 mm at each grid point ending at 0000 UTC 30 Jun 2013 for the operational University of Washington EnKF data assimilation system (RTENKF) and a similar system that also assimilates smartphone observations (PNET). An exclusion radius of 40 km was used to isolate independent maxima. The 10-mm 3-h precipitation derived from the PDT radar is also outlined. More ensemble members indicated a maximum of precipitation near an observed convective location when smartphone pressures were assimilated.

LOOKING TOWARD THE FUTURE.

During the next few years, the number of smartphones/tablets with pressure sensors should increase into the tens of millions over North America and the hundreds of millions globally. If private sector firms or other organizations can develop the infrastructure to "harvest" and share these pressure observations in real time, there could be a substantial improvements in the quality of the initializations of high-resolution numerical weather prediction models and their subsequent forecasts for a wide range of important weather features such as severe convection. Initial research on the impacts of networks of surface pressure observations on mesoscale prediction (e.g., Wheatley and Stensrud 2010; Madaus et al. 2014) suggest that ensemble-based mesoscale data assimilation may offer an attractive approach to securing maximum benefit from smartphone and other pressure observations, but considerably more testing and experimentation is needed, including understanding the relative value of pressure and pressure change assimilation. Furthermore, better approaches for quality control and bias correction of smartphone pressures can enhance the value of these new observation sources. During the next decade a large number of pressure observations from vehicles will likely join the current smartphone collection as transportation platforms gain Internet connectivity. The combination of smartphone and vehicle surface pressure observations may well contribute to a substantial increase in our ability to describe and forecast the atmosphere at high resolution, with substantial economic benefits and the potential to save lives and property.

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REFERENCES

Anderson, J., T. Hoar, K. Raeder, H. Liu, N. Collins, R. Torn, and A. Avellano, 2009: The data assimilation research testbed: a community facility. *Bull. Amer. Meteor. Soc.,* **90,** 1283–1296.

Dirren, S., R. Torn, and G. Hakim, 2007: A data assimilation case study using a limited-area ensemble Kalman filter. *Mon. Wea. Rev.,* **135,** 1455–1473, doi:10.1175/MWR3358.1.

Madaus, L. E., G. J. Hakim, and C. F. Mass, 2014: Utility of dense pressure observations for improving mesoscale analyses and forecasts. *Mon. Wea. Rev.,* **142,** 2398–2413, doi:10.1175/MWR-D-13-00269.1.

Mahoney, W. P., and J.M. O'Sullivan, 2013: Realizing the Potential of Vehicle-Based Observations. *Bull. Amer. Meteor. Soc.,* **94,** 1007–1018.

Overeem, A., H. Leijnse, and R. Uijlenhoet, 2013a: Country-wide rainfall maps from cellular communication networks. *Proc. Natl. Acad. Sci. USA,* **110,** 2741–2745, doi:10.1073/pnas.1217961110.

——, J. C. R. Robinson, H. Leijnse, G. J. Steeneveld, B. K. P. Horn, and R. Uijlenhoet, 2013b: Crowdsourcing urban air temperatures from smartphone battery temperatures. *J. Geol. Res.,* **40,** 4081–4085, doi:10.1002/grl.50786.

Torn, R. D., and G. J. Hakim, 2008: Performance characteristics of a pseudo-operational ensemble Kalman filter. *Mon. Wea. Rev.,* **136,** 3947–3963, doi:10.1175/2008MWR2443.1.

Wheatley, D., and D. Stensrud, 2010: The impact of assimilating surface pressure observations on severe weather events in a WRF mesoscale ensemble system. *Mon. Wea. Rev.,* **138,** 1673–1694, doi:10.1175/2009MWR3042.1.

Whitaker, J., G. Compo, X. Wei, and T. Hamill, 2004: Reanalysis without radiosondes using ensemble data assimilation. *Mon. Wea. Rev.,* **132,** 1190–1200, doi:10.1175/1520-0493(2004)1322.0.CO;2.

ENHANCING CLIMATE RESILIENCE AT NASA CENTERS

A Collaboration between Science and Stewardship

by Cynthia Rosenzweig, Radley M. Horton, Daniel A. Bader, Molly E. Brown, Russell DeYoung, Olga Dominguez, Merrilee Fellows, Lawrence Friedl, William Graham, Carlton Hall, Sam Higuchi, Laura Iraci, Gary Jedlovec, Jack Kaye, Max Loewenstein, Thomas Mace, Cristina Milesi, William Patzert, Paul W. Stackhouse Jr., and Kim Toufectis

NASA has developed a partnership between its Earth scientists and its institutional stewards to prepare for a changing climate and growing climate-related vulnerabilities.

National Aeronautics and Space Administration (NASA) scientists have been instrumental in discovering the nature of weather and climate hazards, yet their agency also has direct experience with their impacts. Power outages and electrical system damage from the tornado outbreak of 27–28 April 2011 closed Marshall Space Flight Center in Huntsville, Alabama, for 10 days. The Station Fire of August–October 2009, which burned a modern-record 250 sq. miles in Los Angeles County, reached within a mile of the Jet Propulsion Laboratory's (California) main campus adjacent to Pasadena (Fig. 1). Air quality concerns closed the Center, and employees, their families, and neighbors experienced evacuations and stress.

Coastal storms are another threat: Hurricane Isabel flooded portions of Langley Research Center (Virginia) in September 2003. Hurricane Frances in 2004 damaged Kennedy Space Center's (Florida)

Fig. 1. Recent climate extremes that have impacted NASA Centers. (a) Hurricane Frances, Sep 2004; (b) Damage to the Vehicle Assembly Building at the Kennedy Space Center from Hurricane Frances in Sep 2004; (c) Station Fire, Sep 2009; (d) Wildfires outside of the Jet Propulsion Laboratory in Sep 2009.

large Vehicle Assembly Building and other Center assets (Fig. 1). Hurricane Katrina in 2005 damaged buildings at Stennis Space Center (Mississippi) and the Michoud Assembly Facility (Louisiana) and displaced thousands of staff (some taking refuge at Stennis for several weeks). Hurricane Ike in 2008 caused flood and wind damage at the Johnson Space Center (Texas), with approximately three-quarters of all roofs sustaining at least minor damage (NASA 2008).

With $32 billion of constructed assets and about 60,000 employees, contractors, and partners, NASA's exposure to weather and climate hazards is not trivial. Its facilities include laboratories, launch sites, airfields, wind tunnels, data centers, and other structures that collectively occupy about 330 square miles, much of it also habitat for threatened and endangered species.

Changing climate alters, and in many cases compounds, the hazards to this infrastructure. The Intergovernmental Panel on Climate Change (IPCC; Field et al. 2012) reports that "it is virtually certain that increases (decreases) in the frequency and magnitude of warm (cold) daily temperature extremes will occur in the 21st century at the global scale." As sea levels, which have increased globally by 0.19 m over the past century (Church et al. 2013), continue to rise, coastal flooding is expected to increase as well (Wong et al. 2014). Two-thirds of NASA's constructed assets are within 5 m of sea level.

In light of such hazards NASA created an agency-wide partnership to better understand and respond to climate risks. In 2009, President Obama issued Executive Order 13514 entitled "Federal Leadership in Environmental, Energy and Economic Performance," which mandates that all U.S. agencies "evaluate agency climate-change risks and vulnerabilities to manage the effects of climate change on the agency's operations and mission in both the short and long term." NASA's program is thus part of the larger federal effort to provide scientific information to support decision-making around climate and weather-related issues (Melillo et al. 2014).

NASA's agency-wide partnership organizes management of climate risks and builds climate resilience at each Center through collaboration between Earth system scientists and institutional stewards (facilities managers, emergency management staff, natural resource managers, and human capital specialists). Thus far, local workshops have facilitated this management by covering planning for climate risks, analysis of climate data and projections for each Center, climate impact and adaptation toolsets, and Center-specific research and engagement. The collaboration between scientists and operations managers established in workshops is now fostering climate resiliency at NASA installations. The way NASA is enhancing resiliency puts its own science to work in a new, internally focused manner that could be a path other science-based agencies, companies, and institutions could implement to instigate their own climate adaptation measures.

Workshop observers from other federal agencies and local partners are now adopting elements of the NASA approach as well. For example, a General Services Administration (GSA)-led multipartner Greengov Spotlight Communities adaptation pilot in the National Capitol Region (www.epa.gov/fgc/spotlight/index.html) has been informed by NASA's adaptation process (Fig. 2) and the climate science information and communication approach developed for NASA's workshops (Ann Kosmal, GSA, 2013, personal communication). Agency neighbors also attend

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NASA workshops, since, as noted in a recent Government Accountability Office (GAO) report, "the climate-related challenges faced by these NASA centers are not unique . . . and can be instructive for other types of large federal facilities." One example is the joint coastal flood risk shared not only by NASA Langley and adjacent Langley Air Force Base, but also by the largest naval complex in the world, located in nearby Norfolk, Virginia (GAO 2013).

Fig. 2. The assessment framework used at the NASA resilience workshops (modified from Rosenzweig and Solecki 2010).

PREPARING FOR CLIMATE CHANGE. A key to this collaborative response is the Climate Adaptation Science Investigator (CASI) Workgroup. Established in 2010, CASI consists of NASA scientists and applications developers (along with additional experts from academia, the private sector, and nongovernmental organizations) who research climate vulnerability at NASA Centers and develop the scientific and technical basis for adaptation (Rosenzweig et al. 2011a).

Like the large cadre of researchers within NASA as well as the broader global science community, CASI members utilize NASA products to understand Earth's climate system, variability and change, and impacts. For example, they use the NASA Goddard Institute for Space Studies (GISS) global climate model (GCM) (Model E; Schmidt et al. 2006) to understand the dynamics of the changing climate; data from the Moderate Resolution Imaging Spectroradiometer (MODIS) along with ecosystem process models to track the impact of land use changes on ecosystem services in the regions where NASA Centers are located (Nemani et al. 2009); and data from the Clouds and the Earth's Radiant Energy System (CERES) (Wielicki et al. 1996) to estimate solar irradiance for modeling energy use and production on NASA buildings.

Through CASI, NASA scientists not only put these products to use, but also learn how their products impact decision-making, which feeds back on their research. Facilities managers at Goddard Space Flight Center, facing more stringent regulation and more intense precipitation events (Horton et al. 2014), have become increasingly focused on stormwater management. CASI scientists have responded by augmenting traditional analysis of how mean precipitation is projected to change with research focused on 1) changes in precipitation intensity and 2) local hydrology, in order to inform the land cover and water flow decisions required to meet regulations.

CASI provides NASA's managers with immediate access to climate and impacts science relevant to their Centers and regions. CASI's partnership of scientists with institutional managers brings together NASA's Earth science expertise and its culture of risk management attained through years of experience in spaceflight and other core missions. NASA's exploration, science, and aerospace technology work necessarily involves risk. In response to both its successes and failures—some of which included a weather-related component—NASA's leadership culture focuses on program risk management. U.S. space vehicle programs and spaceport operations have managed risks by incorporating them into design specifications, mission planning, operations, and decision-making processes (Alcorn et al. 2008).

Olga Dominguez, former Associate Administrator for NASA's Office of Strategic Infrastructure, recounts her experience in learning to communicate stewardship issues with Agency leadership. "I chose the language of risk—the risk the institution bears to the Mission if not adequately managed. Aligning communications patterns with leadership's intent that the NASA Mission comes first, is helping NASA's institutional stewards to set their priorities and receive the consideration they merit."

Climate resilience workshops. Through site-specific climate resilience workshops at NASA Centers, CASI engages internal and external stakeholders in identifying and understanding past, present, and future climate hazards and opportunities, characterizing risks, exploring responses, and developing efficient, sustainable management strategies.

To date, these workshops have initiated climate adaptation for over half of NASA's on-site staff, four-fifths of its managed land, and two-thirds of its constructed assets (Table 1). About 80 internal and external stakeholders participate in each workshop, including Center leadership, Earth scientists, and the institutional stewards. Similarly, external stakeholders (utility providers, community planners, and other interested neighbors) share their climate assessment and adaptation experiences and perspectives.

Each workshop follows an eight-step adaptation assessment process (Fig. 2) with breakout groups focusing on built systems, natural resources, and human populations. Built systems include buildings, test facilities, infrastructure, and utilities, while natural resources encompass storm and surface water, wildlife, air quality, and land use. The human population issues—emergency preparedness, health and safety, and human capital management—are faced by those working on and living near the installation. This adaptation process was extended from an infrastructure-oriented adaptation assessment in New York City (Rosenzweig and Solecki 2010; Major and O'Grady 2010; Rosenzweig et al. 2011b; NRC 2011). While early NASA workshops devoted approximately equal time to each of the eight steps, most workshop breakout time is now devoted to steps 1–4, since these steps lend themselves to immediate climate risk and adaptation brainstorming by a diverse group of participants.

Workshops catalyze the incorporation of climate hazard information and adaptation solutions into post-workshop management plans and processes (steps 5–7). For example, post-workshop activities at Langley Research Center have included 1) storm-hardening projects (focused on protecting buildings and electrical substations, upgrading HVAC systems and utility tunnels, and building or enhancing perimeter flood barriers for facilities on the Center's vulnerable eastern wing; 2) designing and implementing a new 22-kilovolt (KV) redundant electrical loop distribution system to improve electrical system reliability and maintainability by gradually eliminating antiquated 2.4-KV and 6.9-KV infrastructure; and 3) improving understanding of flood vulnerability by performing a lidar-based topographic survey with new elevation measurements for Langley Research Center facilities, and refining a flood impact analysis and visualization tool. Because the climate change adaptation process is iterative, all adaptation strategies must be reevaluated through time, which makes the development of an effective indicators and monitoring system (step 8) critical. Iterations need to take into account how the climate system is changing, impacts being observed, and improved understanding of adaptation strategies and their effectiveness.

Table 1. NASA's climate resilience workshop coverage of on-site staff participation, land managed, and constructed assets.

Share of NASA's assets covered by climate resilience workshops (%)				
Installation	**Workshop**	**On-site staff (%)**	**Land managed (%)**	**Constructed assets (%)**
Agency-wide	**7/2009**	**58,000**	**330 mi^2**	**$32 B**
Kennedy Space Center, FL	5/2010	12.1	66.4	18.5
Ames Research Center, CA	2/2011	7.8	1.0	15.1
Dryden Flight Research Center, CA*	8/2011	2.4	0.4	1.2
Langley Research Center, VA	9/2011	6.4	0.4	11.3
Johnson Space Center, TX	3/2012	12.7	0.8	7.0
Stennis Space Center, MS	10/2012	7.1	9.9	9.4
Wallops Flight Facility, VA	11/2012	1.7	2.9	2.8
Total through 2012 **		***50.2***	***81.8***	***65.3***

* As of March 1, 2014, Dryden Flight Research Center has been renamed Armstrong Flight Research Center

** Total reflects the 7 Center workshops

Climate observations and projections. CASI's climate researchers analyze observed climate trends and make projections for all NASA Centers. Most Centers show statistically significant (99%) warming trends since the beginning of the twentieth century[1] and all coastal Centers show significant (99%) sea level rise trends (Tables 2 and 3), mirroring global and national trends (Stocker et al. 2013; Mellilo et al. 2014).

Because climate variability and change will impact each Center differently, CASI tailors climate projections to each location. These regional temperature and precipitation projections are based on dynamical and statistical downscaling of GCM outputs.[2] Sea level rise and coastal flooding projections are based on both a GCM approach similar to that in Solomon et al. (2007) and a rapid ice-melt scenario as described in Horton and Rosenzweig (2010).

Regional climate model (RCM) projections from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009) indicate average annual temperatures will climb faster this century than last. Averaged across eight GCM-RCM pairings under the high greenhouse gas emissions A2 scenario (Nakicenovic et al. 2000), projected warming by the 2050s relative to the 1980s ranges from 1.9°C at Ames Research Center in Moffett Field, California, to 2.6°C at Glenn Research Center in Cleveland, Ohio, with a 10-Center average of 2.2°C warming (Fig. 3).

The RCMs also project that yearly maximum temperatures will increase more than the summer mean temperatures at all Centers except Ames[3] (Fig. 3). This suggests that for most Centers, increases in the frequency of extreme heat events could exceed projected levels based on a common approach that applies a uniform warming factor from climate models to historical data (Tables ES2).[4] Additionally, the coldest temperatures per year are projected to increase more

Table 2. Observed temperature trends at NASA Centers. Data are for the nearest climate stations going back to the beginning of the twentieth century; all temperature trends are for the 1901–2008 period.

Center	Weather station	Temperature trend (°C decade^{-1})
Ames Research Center	Livermore, CA	0.16*
Dryden Flight Research Center	Fairmont, CA	0.10*
Glenn Research Center	Oberlin, OH	0.03
Goddard Space Flight Center	Beltsville, MD	0.20*
Jet Propulsion Laboratory	Pasadena, CA	0.18*
Johnson Space Center	Liberty, TX	0.04
Kennedy Space Center	Titusville, FL	0.07*
Langley Research Center	Norfolk, VA	0.21*
Marshall Space Flight Center	Huntsville, AL	–0.03
Stennis Space Center	Waveland, MS	0.06*

* Trend that demonstrates 99% significance

Table 3. Observed sea level rise* trends at NASA Centers. Data are for the nearest tide gauges with the longest data record available through 2008. Length of data record: Ames Research Center (1901–2008), Johnson Space Center (1910–2008), Kennedy Space Center (1913–2008), Langley Research Center (1930–2008), and Stennis Space Center (1924–2008).

Center	Tide gauge	Sea level rise trend (mm decade^{-1})
Ames Research Center	San Francisco, CA	19.3**
Johnson Space Center	Galveston, TX	63.6**
Kennedy Space Center	Key West, FL	22.6**
Langley Research Center	Sewells Point, VA	45.2**
Stennis Space Center	Pensacola, FL	21.8**

* Sea level rise is driven by a range of factors, including land subsidence
** Trend that demonstrates 99% significance

[1] Marshall Space Flight Center is in the southeast, one of only a few land regions globally with long-term temperature records that do not show warming over the twentieth century (Hartmann et al. 2013).

[2] Regional climate models (RCMs) are from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al. 2007, 2009). Statistical downscaling is based on the bias corrected spatially disaggregated (BCSD; Maurer et al. 2007) Coupled Model Intercomparison Project phase 3 (CMIP3) dataset. See supplemental material for more information about methods, additional projections, and uncertainties.

[3] These regional climate model simulations are for the A2 emissions scenario for a 30-yr hindcast period and for a 30-yr future period centered on the 2050s.

[4] This approach is known as the delta method (e.g., Gleick 1986; Arnell 1996; Wilby et al. 2004).

than mean winter temperatures for all Centers except Johnson and Stennis on the Gulf Coast.

These projections strengthen the argument that NASA Centers and other institutions should focus on extreme events in their climate risk management. For example, more extreme heat events could have outsized impacts on employee health and safety, while less extreme cold events would reduce the frequency of cold weather-related operations delays and thus reduce damage to infrastructure caused by freeze/thaw cycles.

Sea level rise of between 13 and 69 cm by the 2050s is projected for NASA's five coastal Centers and facilities along the coast (Table ES1).[5,6] CASI applied these sea level rise projections to historical hourly tide gauge data (as in Horton et al. 2010) to determine

[5] Sea level projections are regionalized using the method described in Horton et al. (2011); this approach, which includes regional and global terms, produces lower GCM-based projections (Solomon et al. 2007) as well as a rapid ice-melt scenario that is consistent with recent higher projections (e.g., Pfeffer et al. 2008; NRC 2012; Parris et al. 2012; Perrette et al. 2013; Slangen et al. 2014).

[6] The large range reflects uncertainty related to future rates of melting of land-based ice, primarily the Greenland and West Antarctic Ice Sheets (Rignot et al. 2011, 2014; Vermeer and Rahmstorf 2009; Van den Broeke et al. 2011; Joughin et al. 2014). Variations in sea level rise projections across Centers are small, and relate primarily to changes in land elevation due to glacial isostatic adjustment (Peltier 2001); extraction of groundwater, tectonics, and sediment transport among other factors (Lambeck et al. 2010; González and Tornqvist 2006; Dokka 2011; Shinkle and Dokka 2004); and differences in relative ocean height caused by factors including changes in ocean currents such as the Gulf Stream (Yin et al. 2009, 2010; Horton et al. 2011; Sallenger et al. 2012). Possible gravitational/isostatic/rotational changes as ice sheet mass is reduced (Mitrovica et al. 2001, 2009) were not included.

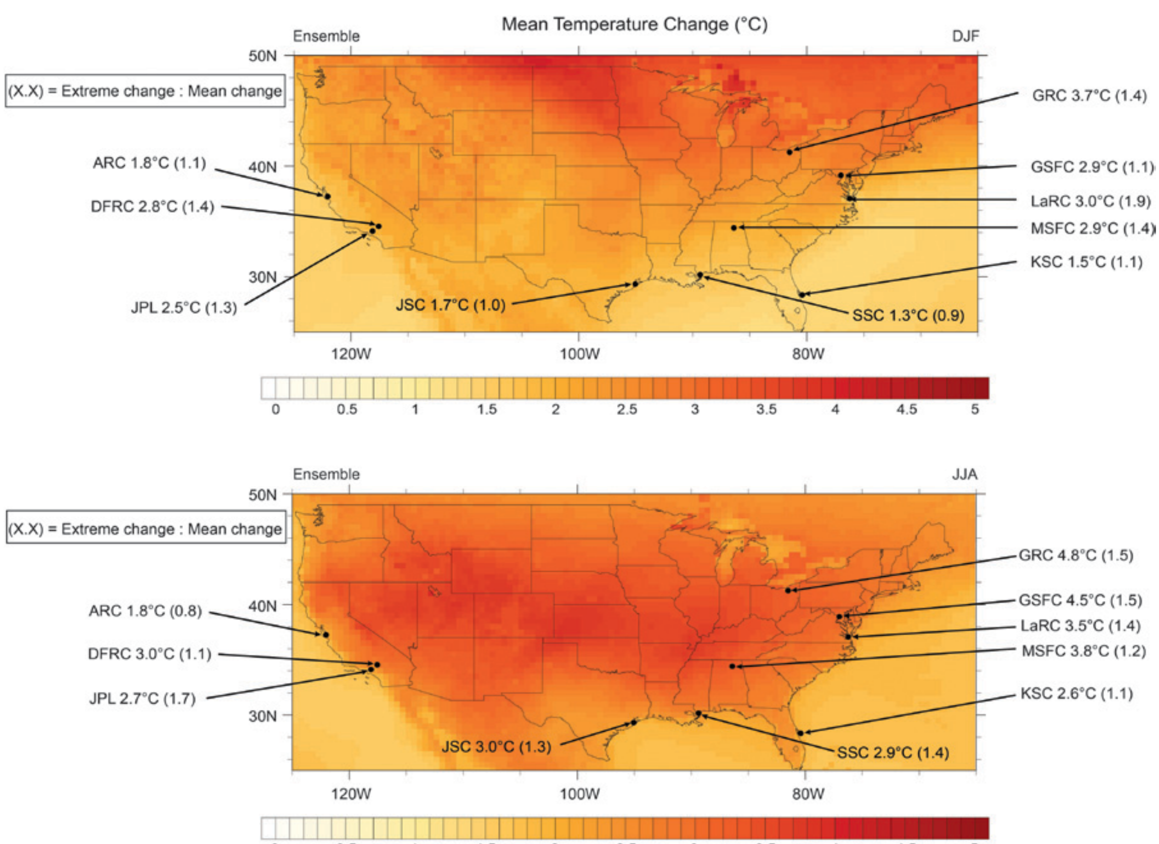

Fig. 3. Mean temperature changes (°C) for (top) winter (DJF) and (bottom) summer (JJA) for the 2050s A2 emissions scenario relative to the 1980s base period for an ensemble of eight GCM-RCM pairings from NARCCAP. For each NASA Center, the number to the right of the Center name is the projected temperature change (°C) in the coldest day per year (top) and hottest day per year (bottom). The number in parentheses is the ratio of the change in coldest (hottest) day relative to the mean changes for winter (summer).

how much sea level rise alone would modify the frequency of future coastal flooding events. Even under lower sea level rise scenarios, the coastal flood event that currently occurs on average once every 10 years is projected to occur approximately 50% more often by the 2050s in the Galveston/Johnson Space Center area; 2 to 3 times as often near Langley Research Center and Kennedy Space Center; and 10 times more frequently in the San Francisco Bay/Ames Research Center area. NASA coastal Centers that are already at risk of flooding are virtually certain to become more vulnerable in the future.

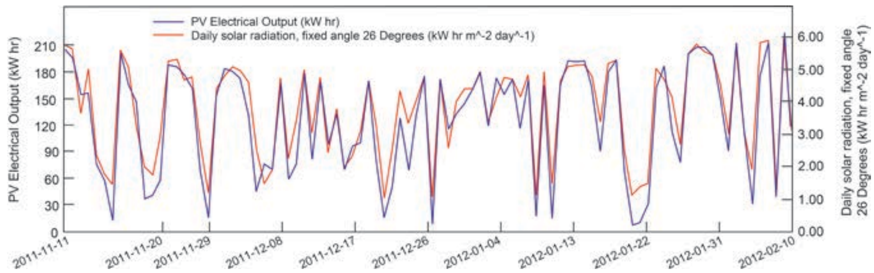

Fig. 4. Output from the RETScreen Plus software system showing the agreement between CERES FLASHFlux daily averaged surface solar flux (adjusted to the solar panel tilt angle) vs Solar Panel Electrical Output for a solar photovoltaic (PV) system attached to a building at the Langley Research Center. The RETScreen Plus tool is designed to provide monitoring, targeting, and verification analysis for renewable energy and energy-efficient technologies. (Figure courtesy of Gregory J. Leng and Urban Ziegler, RETScreen International.)

Climate impact and adaptation toolsets. CASI scientists are developing climate impact and adaptation tools to support Center decision-making related to energy, hydrology, and ecosystems.

CASI energy specialists are collaborating with Natural Resources Canada's RETScreen International team to model energy balance at NASA buildings, including production (e.g., solar power generation) and demand. Using NASA satellite and modeling data products as input, the newly developed RETScreen Plus energy management software monitors current systems, targets future energy efficiency goals using new technologies for existing or new structures, and verifies the result of any system change. CASI and RETScreen assessed the performance of a 39.5 kilowatt (kW) building-level solar panel system at NASA Langley Research Center. Analysis showed high correlation between solar irradiance[7] and the solar panel system electrical output (see Fig. 4). This energy assessment helped to refine system specifications, linked fluctuations in building energy use to atmospheric aerosols from a nearby forest fire, and related system performance to average solar conditions. CASI is incorporating climate projections into the analysis to assess the efficacy of mitigation and adaptation strategies for Langley Research Center buildings, such as solar power and building retrofits for energy efficiency. It also plans to use RETScreen Plus at other Centers to contribute to the development of their own energy-related climate change mitigation and adaptation strategies.

CASI hydrologists and ecologists are using NASA's Terrestrial Observation and Prediction System (TOPS; Nemani et al. 2009) model to analyze projected changes in hydrology and vegetation productivity at the Ames Research Center. TOPS integrates ground observations of climate and physical land cover conditions with NASA satellite observations and climate model projections. Downscaled climate projections from CASI are being combined in TOPS with land-use change scenarios of projected urban growth for two California watersheds: the Coyote Watershed, in which Ames is located, and the Upper Tuolumne Watershed, which contains the Center's water-supply reservoir (the Hetch Hetchy Reservoir) (Fig. 5a). In the Coyote Watershed, where up to a 60% increase in impervious surface area is projected by 2100 under a high-development urban growth scenario (Bierwagen et al. 2010), an increase in winter runoff is projected, and hence an increase in flood risk. In the Upper Tuolumne Watershed, located in the Sierra Nevada of California, projected warming as well as decreasing spring precipitation may cause earlier snowmelt and lead to runoff peaking up to two months earlier by the end of the century. This results in a shorter projected growing season (measured in terms of gross primary production, or GPP, an indicator of vegetation growth) and implies reduced water availability for Ames and an increase in energy costs (given the importance of hydropower) for the region (Fig. 5b).

Center-specific research and engagement. One of NASA's strengths is the diversity of skills across its

[7] Based on NASA CERES Fast Longwave and Shortwave Radiative Fluxes (FLASHFlux) data.

field installations. By conducting coordinated climate risk and adaptation research and engagement at its many facilities, NASA is able to address both unique and shared vulnerabilities. The sidebar titled "Kennedy Space Center and Space Coast Case Study" highlights ongoing activities at Kennedy Space Center and the surrounding region in Florida in recognition of the Center's importance to NASA and its vulnerability to climate hazards.

ADAPTATION AT NASA CENTERS. By developing climate adaptation strategies for local risks and impacts, NASA Center managers are able to reduce the negative effects of climate extremes and climate change. The following examples highlight specific adaptation strategies underway.

At Goddard Space Flight Center in Greenbelt, Maryland, situated in the Chesapeake Bay watershed, extreme precipitation, flooding, and stormwater management are major concerns. In response, grassy areas that previously required mowing are being replaced with natural vegetation and trees to reduce water flows into storm drains during high-intensity rainstorms. Additionally, rain gardens at key drainage points lower stormwater runoff from parking lots and filter the water that flows into storm drains. Together, these efforts will reduce the amount of polluted water that flows from the Center into Chesapeake Bay. Integrating projections of climate change into planning will help ensure that new projects will comply with stormwater regulations in the future.

Ames Research Center is responding to the risk of decreasing water availability by reducing overall water use and maximizing local water sources. Groundwater recovered as part of site-remediation efforts is recycled for cooling some research facilities, such as the Arc Jet and Unitary Wind Tunnel. Reclaimed water from a local wastewater treatment facility is used to irrigate grassy areas, while other landscapes have been converted to native, drought-tolerant plants. The Center has also transitioned to low-flow fixtures through a Utility Energy Services Contract. In response to the prospects of higher energy prices due to increased demand (in part for air conditioning as summer temperatures rise) and reduced hydropower availability, Ames has constructed a top-level (Platinum) Leadership in Energy and Environmental Design

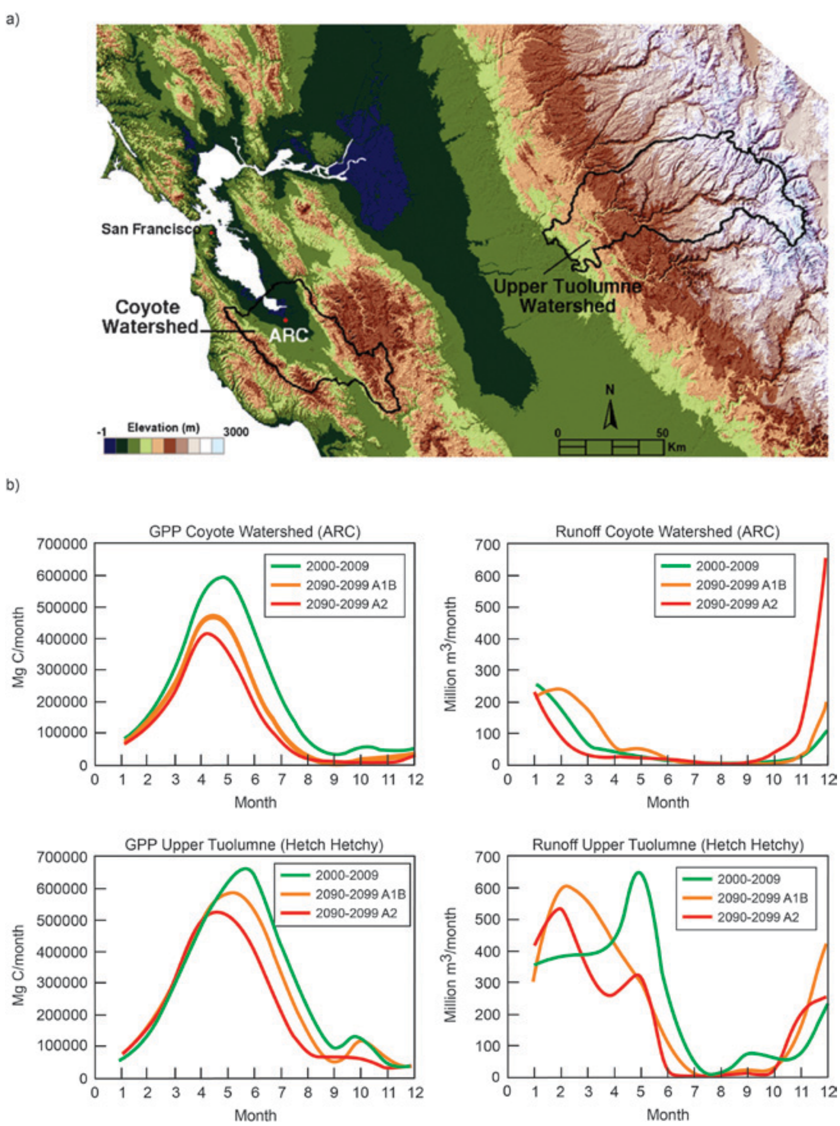

Fig. 5. (a) NASA Terrestrial Observation and Prediction System (TOPS) simulations for Coyote and Tuolumne (Hetch-Hetchy) watersheds. (b) In the Coyote watershed, as the biomass [gross primary productivity (GPP)] decreases, surface runoff increases. In the Upper Tuolumne watershed, warming is associated with a large decrease in biomass (GPP) and an earlier growing season. With earlier snowmelt, earlier runoff is projected, thus exacerbating summer drought risk.

KENNEDY SPACE CENTER AND SPACE COAST CASE STUDY

NASA began its climate adaptation work at the Kennedy Space Center (KSC) for several reasons. Its launch responsibilities are not broadly duplicated elsewhere, and its constructed assets would cost more to replace than at any other NASA site. Furthermore, extreme weather events have demonstrated its vulnerability to climate hazards since sand dunes that both protect KSC's launch pad sites and provide nesting sites for endangered sea turtles are periodically breached by nor'easters and hurricanes.

Assets at stake. Kennedy Space Center (which includes the Merritt Island National Wildlife Refuge) is adjacent to both the Cape Canaveral Air Force Station and the Canaveral National Sea Shore along Florida's east coast. The region has high biodiversity, rich ecosystem services, and national assets for assured access to space valued at roughly $10.9 billion (Breininger et al. 1998; T. Carlson 2012, personal communication; D. George 2012, personal communication). These structures include space vehicle launch and landing facilities, numerous vehicle and payload-processing facilities, fuel-handling systems, and industrial and office complexes. Tourism and recreation in the area, associated with KSC and the abundant natural resources of the Indian River Lagoon, have been valued at more than $3.7 billion annually (Hazen and Sawyer 2008). Using CASI sea level rise projections (Fig. SB1), NASA has identified a broad range of vulnerabilities, including facilities and structures, transportation, communications, energy, drinking water, wastewater, and solid waste systems, as well as protected species habitats and archaeological sites (Dewberry 2009; NASA 2010; Industrial Economics 2011).

Priority research activities. CASI is embarking on studies at KSC based on research and data needs identified in partnership with its management personnel. Topics include changes in extreme events and their impacts on launch hardware processing activities; heat indices and impacts on workforce and work scheduling; and effects of sea level rise and changing hydrological conditions on water table depth, a factor that influences plant community distributions, protected species wildlife habitats, and potential redistribution of chemical contaminants. Additionally, NASA-funded academic and private-sector teams are now working with CASI at KSC to investigate climate impacts on local mangrove populations, launch criteria, and sea level rise.

Interactions with area stakeholders. Recognizing the importance of information-sharing and regional coordination, CASI scientists and Kennedy Space Center managers have engaged with land managers from the U.S. Air Force, U.S. Fish and Wildlife Service, St. Johns River Water Management District, and the Environmental Protection Agency (EPA) Indian River Lagoon National Estuaries Program to discuss issues associated with wetlands and protected species habitats in the region. For example, after attending KSC's climate resilience workshop, Air Force staff of the 45th Space Wing began expanding evaluations of climate change risks and projected sea level rise impacts along the Space Coast as part of their management and planning responsibilities at both Patrick Air Force Base and the Cape Canaveral Air Force Station, adjacent to Kennedy Space Center. These evaluations include consideration of new facility designs that protect electronics and computers from storm surge, and land use plans that would site new construction away from the beach and dune area along the coast (D. George 2012, personal communication).

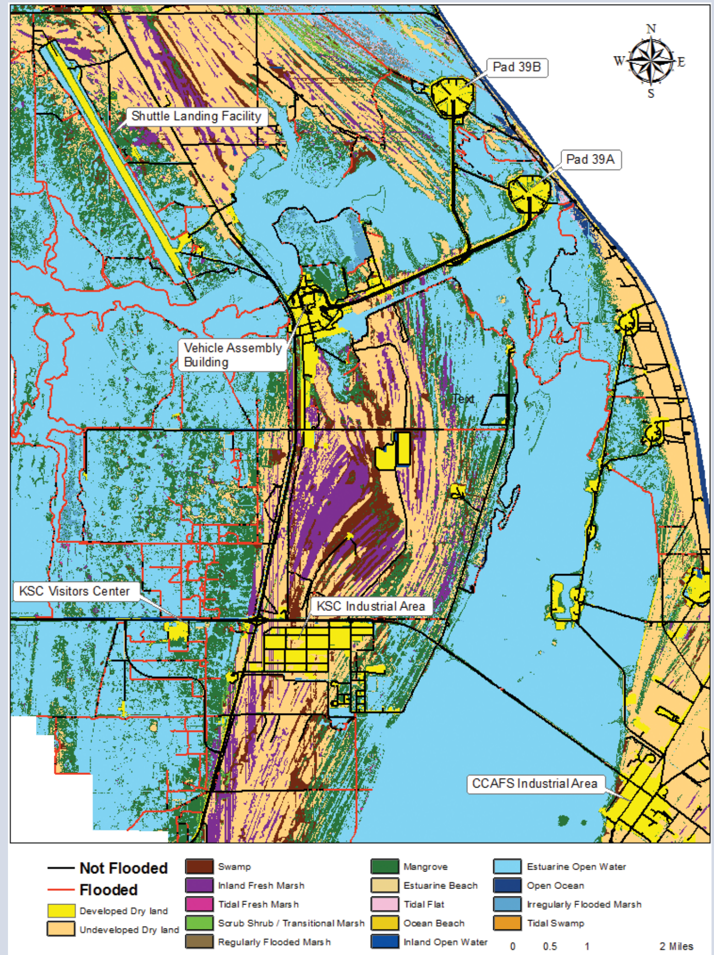

Fig. SB1. Potential flooding in the KSC environs based on the Sea Level Affecting Marshes Model (SLAMM) under a 1.2-m (NAVD88) sea level rise scenario. SLAMM output was developed in conjunction with the EPA Indian River Lagoon National Estuaries Program and Industrial Economics, Inc. (2011) utilizing CASI-developed climate change scenarios for KSC. In this scenario, most current wetlands in the region convert to open water and mangrove forest. Road inundation, during the annual fall period of maximum monthly mean sea levels, includes 11.5%, 30.5%, and 60% of primary (main arteries), secondary (paved), and tertiary (unpaved) roads, respectively. These roads are at or below 1.2-m elevation, so any combination of sea level rise, storm surge, wave-induced runup, and wind-driven seiches (standing waves) that raise the lagoon level to 1.2 m will inundate these areas. Duration of inundation will depend on magnitude and duration of individual events. These event-based inundations are projected to increase in frequency and magnitude as sea level rises from current elevation.

(LEED) building that provides both climate change adaptation and mitigation benefits. The CASI Ames team now coordinates with local agencies including the Fish and Wildlife Service, U.S. Geological Survey (USGS), Army Corps of Engineers, and Santa Clara County Water District.

At the Kennedy Space Center, coastal storms have been an ever-present hazard since NASA purchased 200 square miles of land in 1961, north and west of the Air Force launch pads at Cape Canaveral. Now, a Dune Vulnerability Team is addressing potential sea level rise and future storm-surge impacts to coastal facilities and infrastructure at Kennedy Space Center, especially Launch Pads 39A and 39B, which have played a critical role in space flight programs (NASA 1978, 2010). The Dune Vulnerability Team is designing an engineering approach to managing coastal erosion and preparing an environmental assessment under the National Environmental Policy Act (NEPA). Options to provide long-term protection of the launch sites include construction of a three-mile secondary inland dune, and dune and beach nourishment (NASA 2012). Climate risks have also been factored into the master planning process for ongoing twenty-first century spaceport facilities modifications and upgrades and the Kennedy Space Center 2012–2031 Future Development Concept (available online at http://kscpartnerships.ksc.nasa.gov/documents/KSC_FDC_Brochure.pdf). Finally, the Kennedy Space Center Sustainability Program is incorporating climate risk information in the planning process for facilities designs to address energy efficiency (NASA 2012).

CONCLUSIONS AND NEXT STEPS. While building climate resiliency at NASA is a long-term process, early CASI interactions and results hold promise. CASI strengthens the science community's commitment to understanding climate impacts, targets research to the needs of NASA institutional stewards, and equips those stewards through workshops and ongoing knowledge-sharing with a basis for proactive risk management.

The Agency's scientist–steward partnership reflects its commitment to deliver value to local communities as well as nationally and globally. NASA shares common resources including water and infrastructure with these communities. Sharing of climate risk information and coordinated planning in the broader areas where NASA Centers are located contribute to the development of regional climate resilience over the long term. Supporting a productive workforce depends on the well-being and climate preparedness of families, neighbors, homes, schools, and services.

Next steps for CASI involve both scientists and stewards. Scientists are integrating the newer global climate model [phase 5 of the Coupled Model Intercomparison Project (CMIP5)] results into the existing [phase 3 (CMIP3)] projection framework. It is also critical to advance understanding of why extreme climate events are projected to change. For example, how are extreme temperature projections influenced by changes in atmospheric dynamics (Liu et al. 2012) and the land surface (Seneviratne et al. 2010)? Researchers are also investigating how impacts of extreme events may change due to nonclimatic factors (e.g., population growth and land management). Next-generation sea level rise and storm surge projections are integrating advances in geodesy (Nerem et al. 2010), improved understanding of ice sheets and glaciers (Bamber and Aspinall 2013; Radic et al. 2014), and the global impacts of land water storage (Pokhrel et al. 2012).

On the stewardship side, site-specific workshops are helping the agency integrate efforts across its workforce, its natural systems, and its constructed assets with an emphasis on involving stakeholders from beyond NASA's fencelines. Future workshops may also focus on specific climate hazards and impacts. Additional management efforts include integrating climate risk and resilience into each Center's master plan. These initiatives catalyze integration of climate risk management into ongoing short- and long-term decision-making at NASA.

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REFERENCES

Alcorn, J. M., C. Rosenzweig, R. Horton, and I. S. Higuchi Jr., 2008: U.S. space transportation and climate change: Potential impacts of climate change on access to space. *Proc. 11th Int. Conf. on Engineering, Science, Construction, and Operations in Challenging Environments*, Long Beach, CA, American Society of Civil Engineers, doi:10.1061/40988(323)130.

Arnell, N. W., 1996: *Global Warming, River Flows, and Water Resources*. Wiley, 234 pp.

Bamber, J. L., and W. P. Aspinall, 2013: An expert judgement assessment of future sea level rise from the ice sheets. *Nat. Climate Change,* **3,** 424–427, doi:10.1038/nclimate1778.

Bierwagen, B. G., D. M. Theobald, C. R. Pyke, A. Choate, P. Groth, J. V. Thomas, and P. Morefield, 2010: National housing and impervious surface scenarios for integrated climate impact assessments. *Proc. Natl. Acad. Sci. USA,* **107,** 20 887–20 892, doi:10.1073/pnas.1002096107.

Breininger, D. R., M. J. Barkaszi, R. B. Smith, D. M. Oddy, and J. A. Provancha, 1998: Prioritizing wildlife taxa for biological diversity conservation at the local scale. *Environ. Manage.,* **22,** 315–321, doi:10.1007/s002679900107.

Church, J. A., and Coauthors, 2013: Sea Level Change. *Climate Change 2013: The Physical Science Basis*. T. F. Stocker, et al., Eds., Cambridge University Press, 1535 pp. [Available online at www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf.]

Dewberry, 2009: LiDAR, Breaklines and Contours for Brevard County, Florida. Final Report of Specific Purpose LiDAR survey. State of Florida Division of Emergency Management, Contract 07-HS-34-14-00-22-469, and Add-On Agreement with Brevard County, Florida. [Available online at ftp://csc.noaa.gov/pub/DigitalCoast/lidar1_z/geoid12a/data/558/supplemental/Survey_Report_for_Brevard_County_FL.pdf.]

Dokka, R. K., 2011: The role of deep processes in late 20th century subsidence of New Orleans and coastal areas of southern Louisiana and Mississippi. *J. Geophys. Res.,* **116,** B06403, doi:10.1029/2010JB008008.

Field, C. B., V. Barros, T. F. Stocker, and Q. Dahe, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge University Press, 582 pp.

GAO, 2013: Climate change: Future federal adaptation efforts could better support local infrastructure decision makers. United States Government Accountability Office (GAO) Rep. 13-242, 87 pp. [Available online at www.gao.gov/products/gao-13-242.]

Gleick, P. H., 1986: Methods for evaluating the regional hydrologic effects of global climate changes. *J. Hydrol.,* **88,** 97–116, doi:10.1016/0022-1694(86)90199-X.

González, J. L., and T. E. Tornqvist, 2006: Coastal Louisiana in crisis: Subsidence or sea level rise? *Eos, Trans. Amer. Geophys. Union,* **87,** 493–498, doi:10.1029/2006EO450001.

Hartmann, D. L., and Coauthors, 2013: Observations: Atmosphere and Surface. *Climate Change 2013: The Physical Science Basis*. Stocker, T. F., et al., Eds., Cambridge University Press, 1535 pp.

Hazen and Sawyer, 2008: Indian River Lagoon Economic Assessment and Analysis Update. Indian River Lagoon National Estuary Program. Final Report, Contract 24706, Hazen and Sawyer, P.C., 211 pp.

Horton, R., and C. Rosenzweig, 2010: Climate risk information. *Climate Change Adaptation in New York City: Building a Risk Management Response,* C. Rosenzweig and W. Solecki, Eds., New York Academy of Sciences, 148–228.

——, V. Gornitz, M. Bowman, and R. Blake, 2010: Climate observations and projections. *Climate Change Adaptation in New York City: Building a Risk Management Response,* C. Rosenzweig and W. Solecki, Eds., New York Academy of Sciences, 41–62.

——, ——, D. A. Bader, A. C. Ruane, R. Goldberg, and C. Rosenzweig, 2011: Climate hazard assessment for stakeholder adaptation planning in New York City. *J. Appl. Meteor. Climatol.,* **50,** 2247–2266, doi:10.1175/2011JAMC2521.1.

——, and Coauthors, 2014: Northeast. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 829 pp., doi:10.7930/J0SF2T3P.

Industrial Economics, 2011: The impacts of sea level rise to the Indian River Lagoon Estuary (Florida): An application of ecological and economic models. Industrial Economics, Inc., final report, prepared for U.S. Environmental Protection Agency Climate Change Division and the Indian River Lagoon National Estuaries Program, 122 pp.

Joughin, I., B. E. Smith, and B. Medley, 2014: Marine ice sheet collapse potentially underway for the Thwaites Glacier Basin, West Antarctica. *Science,* **344,** 735–738, doi:10.1126/science.1249055.

Lambeck, K., C. D. Woodroffe, F. Antonioli, M. Anzidei, W. R. Gehrels, J. Laborel, and A. J. Wright, 2010: Paleoenvironmental records, geophysical modeling, and reconstruction of sea-level trends and variability on centennial and longer timescales. *Understanding Sea-Level Rise and Variability,* J. A. Church et al., Eds., Blackwell, 61–121.

Liu, J. P., J. A. Curry, H. J. Wang, M. R. Song, and R. M. Horton, 2012: Impact of declining Arctic sea ice on winter snowfall. *Proc. Natl. Acad. Sci. USA,* **109,** 4074–4079, doi:10.1073/pnas.1114910109.

Major, D. C., and M. O'Grady, 2010: Adaptation assessment guidebook. *Climate Change Adaptation in New York City: Building a Risk Management Response,* C. Rosenzweig and W. Solecki, Eds., New York Academy of Sciences, 229–292.

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy, 2007: Fine-resolution climate projections enhance regional climate change impact studies. *Eos, Trans. Amer. Geophys. Union,* **88,** 504, doi:10.1029/2007EO470006.

Mearns, L. O., and Coauthors, 2007 (updated 2012): The North American Regional Climate Change Assessment Program dataset. National Center for Atmospheric Research Earth System Grid data portal. [Available online at www.narccap.ucar.edu.]

——, W. Gutowski, R. Jones, R. Leung, S. McGinnis, A. Nunes, and Y. Qian, 2009: A regional climate change assessment program for North America. *Eos, Trans. Amer. Geophys. Union,* **90,** 311, doi:10.1029/2009EO360002.

Melillo, J, M., T. C. Richmond, and G. W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp, doi:10.7930/J0Z31WJ2.

Mitrovica, J. X., M. Tamisiea, J. L. Davis, and G. A. Milne, 2001: Recent mass balance of polar ice sheets inferred from patters of global sea-level change. *Nature,* **409,** 1026–1029, doi:10.1038/35059054.

——, N. Gomez, and P. U. Clark, 2009: The sea-level fingerprint of West Antarctic collapse. *Science,* **323,** 753, doi:10.1126/science.1166510.

Nakicenovic, N., and Coauthors, 2000: *Special Report on Emissions Scenarios.* Cambridge University Press, 599 pp.

NASA, 1978: Environmental Impact Statement for the Space Shuttle Program. NASA, 256 pp.

——, 2008: Lyndon B. Johnson Space Center: Roundup, Hurricane Ike Edition. [Available online at www.jsc.nasa.gov/roundup/online/2008/1108.pdf.]

——, 2010: Environmental Resources Document. John F. Kennedy Space Center. KSC-PLN-1911, Revision E, 354 pp. [Available online at http://environmental.ksc.nasa.gov/projects/documents/ERDRevE.pdf.]

——, 2012: Kennedy Space Center Sustainability Plan. John F. Kennedy Space Center. KSC-PLN-8553, 52 pp. [Available online at www.nasa.gov/centers/kennedy/pdf/615155main_2012_KSC_Sustainability_Plan_Med_Res.pdf.]

Nemani, R., and Coauthors, 2009: Monitoring and forecasting ecosystem dynamics using the Terrestrial Observation and Prediction System (TOPS). *Remote Sens. Environ.,* **113,** 1497–1509, doi:10.1016/j.rse.2008.06.017.

Nerem, R. S., D. P. Chambers, C. Choe, and G. T. Mitchum, 2010: Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Mar. Geod.,* **33,** 435–446, doi:10.1080/01490419.2010.491031.

NRC, 2011: America's climate choices: Final report. National Research Council, The National Academies Press, 118 pp.

——, 2012: Sea-level rise for the coasts of California, Oregon, and Washington: Past, present, and future. National Research Council, The National Academies Press, 32 pp.

Parris, A., and Coauthors, 2012: Global sea level rise scenarios for the U.S. National Climate Assessment. NOAA Tech. Memo. OAR CPO-1, 29 pp. [Available online at http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf.]

Peltier, W. R., 2001: Global glacial isostatic adjustment and modern instrumental records of relative sea level history. *Sea Level Rise: History and Consequences,* B. C. Douglas, M. S. Kearney, and S. P. Leatherman, Eds., Academic Press, 65–95.

Perrette, M., F. Landerer, R. Riva, K. Frieler, and M. Meinshausen, 2013: A scaling approach to project regional sea level rise and its uncertainties. *Earth Syst. Dyn.,* **4,** 11–29, doi:10.5194/esd-4-11-2013.

Pfeffer, W. T., J. T. Harper, and S. O'Neel, 2008: Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science,* **321,** 1340–1343, doi:10.1126/science.1159099.

Pokhrel, Y. N., N. Hanasaki, P. J-F. Yeh, T. J. Yamada, S. Kanae, and T. Oki, 2012: Model estimates of sea-level change due to anthropogenic impacts on terrestrial water storage. *Nat. Geosci.,* **5,** 389–392, doi:10.1038/ngeo1476.

Radic, V., A. Bliss, A. C. Beedlow, R. Hock, E. Miles, and J. G. Cogley, 2014: Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. *Climate Dyn.,* **42,** 37–58, doi:10.1007/s00382-013-1719-7.

Rignot, E., I. Velicogna, M. R. van den Broeke, A. Monaghan, and J. Lenaerts, 2011: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys. Res. Lett.,* **38,** L05503, doi:10.1029/2011GL046583.

——, J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl, 2014: Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophys. Res. Lett.,* **41,** 3502–3509, doi:10.1002/2014GL060140.

Rosenzweig, C., and W. Solecki, 2010: *Climate Change Adaptation in New York City: Building a Risk Management Response.* New York Academy of Sciences, 354 pp.

——, and Coauthors, 2011a: NASA's CASI: Building Climate-Resilient NASA Centers. *Livebetter Mag.,* Vol. 15 (December 2011). [Available online at http://livebettermagazine.com/article/nasas-casi-building-climate-resilient-nasa-centers/.]

——, and Coauthors, 2011b: Developing coastal adaptation to climate change in the New York City infrastructure-shed: Process, approach, tools, and strategies. *Climatic Change,* **106,** 93–127, doi:10.1007/s10584-010-0002-8.

Sallenger, A. H., K. S. Doran, and P. A. Howd, 2012: Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nat. Climate Change,* **2,** 884–888, doi:10.1038/nclimate1597.

Schmidt, G. A., and Coauthors, 2006: Present-day atmospheric simulations using GISS ModelE: Comparison to in situ, satellite, and reanalysis data. *J. Climate,* **19,** 153–192, doi:10.1175/JCLI3612.1.

Seneviratne, S. I., and Coauthors, 2010: Investigating soil moisture–climate interactions in a changing climate: A review. *Earth Sci. Rev.,* **99,** 125–161, doi:10.1016/j.earscirev.2010.02.004.

Shinkle, K., and R. K. Dokka, 2004: Rates of vertical displacement at benchmarks in the lower Mississippi Valley and the northern Gulf Coast: NOAA Tech. Rep. 50, 135 pp.

Slangen, A. B., M. Carson, C. A. Katsman, R. S. W. van de Wal, A. Köhl, L. L. A. Vermeersen, and D. Stammer, 2014: Projecting twenty-first century regional sea level changes. *Climatic Change,* **124,** 317–332, doi:10.1007/s10584-014-1080-9.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. M. B. Tignor, and H. L. Miller Jr., 2007: *Climate Change 2007: The Physical Science Basis.* Cambridge University Press, 996 pp.

Stocker, T. F., and Coauthors, 2013: *Climate Change 2013: The Physical Science Basis.* Cambridge University Press, 1535 pp.

Van den Broeke, M. R., J. Bamber, J. Lenaerts, and E. Rignot, 2011: Ice sheets and sea level: Thinking outside the box. *Surv. Geophys.,* **32,** 495–505, doi:10.1007/s10712-011-9137-z.

Vermeer, M., and S. Rahmstorf, 2009: Global sea level linked to global temperature. *Proc. Natl. Acad. Sci. USA,* **106,** 21 527–21 532, doi:10.1073/pnas.0907765106.

Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System experiment. *Bull. Amer. Meteor. Soc.,* **77,** 853–868, doi:10.1175/1520-0477(1996)0772.0.CO;2.

Wilby, R. L., S. Charles, E. Zorita, B. Timbal, P. Whetton, and L. Mearns, 2004: Guidelines for use of climate scenarios developed from statistical downscaling methods. IPCC Data Distribution Centre, 27 pp. [Available online at www.ipcc-data.org/guidelines/dgm_no2_v1_09_2004.pdf.]

Wong, P. P., and Coauthors, 2014: Coastal systems and low-lying areas. *Climate Change 2014: Impacts, Adaptation, and Vulnerability.* C. B. Field, et al., Eds., Cambridge University Press, in press. [Available online at http://ipcc-wg2.gov/AR5/report/final-drafts/.]

Yin, J., M. E. Schlesinger, and R. J. Stouffer, 2009: Model projections of rapid sea-level rise on the Northeast coast of the United States. *Nat. Geosci.,* **2,** 262–266, doi:10.1038/ngeo462.

——, S. M. Griffies, and R. J. Stouffer, 2010: Spatial variability of sea level rise in twenty-first century projections. *J. Climate,* **23,** 4585–4607, doi:10.1175/2010JCLI3533.1.


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THE CHUVA PROJECT

How Does Convection Vary across Brazil?

by Luiz A. T. Machado, Maria A. F. Silva Dias, Carlos Morales, Gilberto Fisch, Daniel Vila, Rachel Albrecht, Steven J. Goodman, Alan J. P. Calheiros, Thiago Biscaro, Christian Kummerow, Julia Cohen, David Fitzjarrald, Ernani L. Nascimento, Meiry S. Sakamoto, Christopher Cunningham, Jean-Pierre Chaboureau, Walter A. Petersen, David K. Adams, Luca Baldini, Carlos F. Angelis, Luiz F. Sapucci, Paola Salio, Henrique M. J. Barbosa, Eduardo Landulfo, Rodrigo A. F. Souza, Richard J. Blakeslee, Jeffrey Bailey, Saulo Freitas, Wagner F. A. Lima, and Ali Tokay

CHUVA reveals very diverse cloud processes in tropical continental regions and contributes to improving satellite precipitation estimation, nowcasting, cloud-resolving models, and the understanding of cloud electrification.

The CHUVA project—CHUVA, meaning "rain" in Portuguese, is the acronym for the Cloud Processes of the Main Precipitation Systems in Brazil: A Contribution to Cloud-Resolving Modeling and to the Global Precipitation Measurement (GPM)—began in 2010 and has conducted five field campaigns; the last experiment will be held in Manaus as part of the Green Ocean Amazon (GoAmazon) experiment in 2014 (see http://campaign.arm.gov/goamazon2014/ for a detailed description). CHUVA's main scientific motivation is to contribute to the understanding of cloud processes, which represent one of the least understood components of the climate system.

Brazil has an area of 8.5 million square kilometers and lies primarily south of the equator and within the tropics. Therefore, Brazil is ideally situated for studying tropical continental convection over a broad range of precipitation regimes within a single country. In northeastern Brazil, a semiarid region, the CHUVA project was designed to characterize warm clouds (Costa et al. 2000) and the organized convection influenced by the intertropical convergence zone and easterly waves (Kouadio et al. 2012). Cotton (1982) defines warm clouds as clouds in which the ice phase does not play a substantial role in the precipitation process. In the Amazon, specifically in the Belém and Manaus regions, the main targeted precipitation regimes were tropical squall lines (Cohen et al. 1995); local convection, which is strongly forced by the diurnal cycle (Machado et al. 2002); and mesoscale convective systems (Rickenbach 2004). In southern Brazil, at the boundary of the tropical and subtropical regions, CHUVA measured the convection associated with cold fronts (Garreaud 2000), mesoscale convective complexes (Salio et al. 2007), and strongly electrified convection (Cecil and Blankenship 2012). The field campaigns in each of these regions collected detailed observations of various rainfall regimes over a tropical continental region to improve our understanding of cloud processes. The campaigns focused on the following applications: satellite precipitation estimation, cloud-resolving models, nowcasting, and cloud electrification. CHUVA is contributing to the National Aeronautics and Space Administration (NASA)–Japan Aerospace Exploration Agency (JAXA) GPM, the National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite R-series (GOES-R), and the GoAmazon programs.

Schumacher and Houze (2003) demonstrated large seasonal and regional variability in the stratiform rain fraction (the contribution of stratiform precipitation to the total precipitation) over Brazil using the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR). Precipitation estimation has been noticeably improved by the TRMM and the development of new algorithms (Tapiador et al. 2012). However, precipitation estimation over land using passive radiometers still has several deficiencies. Specifically, precipitation is indirectly estimated (Berg et al. 2006). Moreover, precipitation from warm clouds is largely underestimated, especially when using microwave radiometers, and contributes (7.5% on average) to the total rainfall in tropical coastal regions (Liu and Zipser 2009). Over land, microwave satellite precipitation estimates exploit the relationship between ice aloft and rainfall at the surface. Because these clouds have no ice, the precipitation estimates for warm-cloud rainfall are inaccurate. For example, during November 2008, 283 mm of rainfall, mostly from orographic warm clouds, was measured by rain gauge over 24 h in southeastern Brazil. However, only very light precipitation amounts (approximately 30 mm) were estimated using satellite data (Silva Dias 2009). Williams and Stanfill (2002) discuss the formation of warm-cloud rainfall in the context of cloud condensation nuclei and updrafts and contrast the marine and continental environments.

The passive microwave rainfall sensors used by the GPM constellation to achieve 3-h rainfall estimates have largely relied on ice scattering signals to convert brightness temperature depressions into rainfall rates over continental regions. The CHUVA field campaigns, in addition to their focus on the microphysical properties of tropical clouds, have an important role in improving existing algorithms for precipitation retrieval for the GPM mission. Therefore, an important component of CHUVA was to provide a homogeneous dataset to the community that supports GPM algorithm development in both warm- and cold-phase clouds. As mentioned, warm-rain clouds are particularly challenging for the passive microwave remote sensing of precipitation. CHUVA data will help address this issue.

The dataset collected in this project, combined with cloud modeling, is expected to create a solid basis for the development of improved database on cloud process over the continental tropics. This dataset contains hydrometeor classifications, thermodynamics profiles, rainfall drop size distributions, and several remote sensing (both active and passive) cloud property measurements. Realistic parameterizations of cloud processes are a prerequisite for reliable current and future climate simulations. Meteorological models, at very high resolution, explicitly describe cloud processes to a large degree; however, the cloud microphysics and turbulent processes require parameterization. Morrison and Grabowski (2007) demonstrate the large sensitivity of high-resolution simulations to the microphysical parameterizations. The CHUVA dataset, combining model, satellite, radar, radiometer, and other in situ data, will provide an opportunity to validate and improve cloud-resolving models over various tropical continental regions.

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GOES-R, the next generation of NOAA geostationary satellites, includes a new capability for total lightning detection from the Geostationary Lightning Mapper (GLM). The GLM will aid in forecasting severe storms and tornadic activity and will address convective weather impacts on aviation safety and efficiency (Goodman et al. 2013). The CHUVA measurements provide a high-fidelity dataset for GLM application development in continental tropical regions.

This study outlines the motivation for developing the CHUVA project and general information on the measurement strategy and how to access the database and the project web page. Additionally, this study presents a specific description of each field experiment, a discussion of the preparation for the final campaign, and a summary of the main results and activities for project outreach.

MOTIVATION. CHUVA's principal motivation is the description and understanding of the cloud processes of the various precipitation regimes of Brazil. The expected results include improved satellite precipitation estimates, especially from warm clouds; cloud-resolving model evaluation; development of nowcasting techniques for intense thunderstorms; and an improved understanding of the cloud electrification processes in the tropics and subtropics. The CHUVA project addresses the following questions:

- How can satellite estimates of warm-cloud precipitation be improved?
- How can GPM satellite-based retrievals of rainfall over the continent be improved?
- What are the typical cloud processes that occur in the main precipitation regimes of Brazil?
- What are the major surface and boundary layer processes relevant to the formation and maintenance of clouds?
- What are the primary processes in the evolution from shallow to deep convection, and how do cloud microphysical and electrification processes evolve during this transition and cloud life cycle?
- How can the representation of clouds and accuracy be improved in cloud-resolving models, especially for intense thunderstorms?
- How can all of the acquired knowledge be utilized to improve nowcasting and forecasting in tropical regions?

To answer these questions, the CHUVA project focused on collecting data that describe the multidimensional structure of clouds in different precipitation regimes. These data include 1) the selected cloud properties from X-band dual-polarization radar (X-Pol) and Micro Rain Radar (MRR) data; 2) satellite and radar precipitation fields, cloud-type classification, and cloud and rain cell life cycles; 3) the electric fields and lightning associated with clouds from the lightning network and field mills (an electromechanical device that measures the strength of the electrostatic field at the surface), which are essential for describing thunderstorm electrification processes; and 4) mesoscale atmospheric conditions and surface fluxes from rawinsondes and from towers to assess the atmospheric dynamical and thermodynamic properties. These data are combined with a cloud-resolving model [the Brazilian version of the Regional Atmospheric Modeling System (BRAMS)] to describe the typical cloud processes of the various precipitation regimes. As proposed by Negri et al. (2014), comparing satellite and/or radar measurements with virtual images simulated by radiative transfer and cloud-resolving model outputs can validate the model and create a microphysical database.

These datasets are specifically used to 1) test different methodologies for estimating warm-cloud precipitation; 2) evaluate the possible relationships between integrated ice content, electrification, and precipitation as functions of the cloud life stage; 3) employ different satellite rainfall algorithms and assess the associated regional errors; 4) describe the temporal evolution of the electrical field during thunderstorm development in conjunction with the radar polarimetric variables; 5) investigate the column-integrated atmospheric water vapor during periods preceding intense thunderstorms; and 6) analyze the capability of cloud-resolving models to describe the microphysical properties and the effect of the turbulence parameterization on cloud organization.

EXPERIMENTAL DESIGN. *Sites and measurement strategies.* CHUVA consists of six field campaigns, five of which have already taken place. The sixth will be carried out in 2014 in Manaus as part of the GoAmazon initiative (http://campaign.arm.gov/goamazon2014/). Figure 1 (left) shows the experimental sites of the CHUVA projects and illustrates the main precipitation regime expected in each region. Figure 1 (right) also shows a schematic representation of the measurement strategy employed in the CHUVA campaigns. A primary instrument used for CHUVA is a mobile X-band dual-polarization (dual-pol) radar. Schneebeli et al. (2012) give a detailed description of the radar, operation, and data processing. The

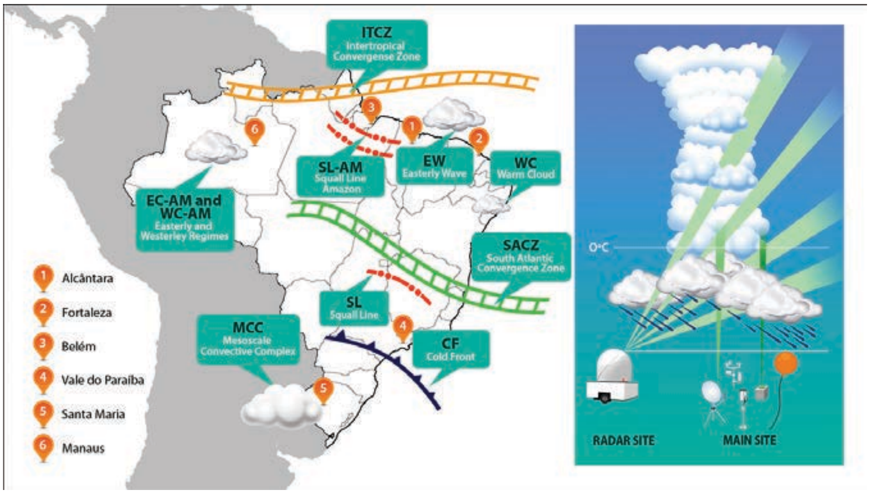

Fig. 1. (left) A description of the CHUVA field campaigns over Brazil and an illustration of the main precipitation regimes. (right) The reference measurement strategy adopted during the field campaigns, along with the radar site and main site with other ground instruments.

radar scan strategy consists of a volume scan with 10–14 elevations (depending on the main type of clouds targeted) and at least one range–height indicator (RHI) scan along the direction of the main instrumentation site. The RHI is performed with an antenna rotation rate of 9° s^{-1}, a high angular resolution (every 0.50°), and a high sampling frequency (obtained using 150 samples per ray) to ensure a high vertical resolution and data accuracy. The entire procedure (strategy) also includes a differential reflectivity (Z_{DR}) offset check using a vertical measurement along the column above the radar. Figure 1 presents a typical description of the measurement strategy. The distance between the radar site and the main site is approximately 20 km; the main site is equipped with the following basic instruments (see Table 1 for a detailed description): impact (Joss–Valdwogel) and laser [OTT Particle Size and Velocity (PARSIVEL) and Thies] disdrometers; rain gauges (tipping bucket employed in a dual-gauge configuration at the main site); and a microwave radiometer (MP3000A with 35 channels) ranging from 22.00 to 30.00 GHz (21 channels), a range associated with water vapor emissions, and from 51.00 to 59.00 GHz (14 channels), a range associated with molecular oxygen emissions (Ware et al. 2003). Additionally, the main site instrumentation includes one vertically pointing K-Band (24.1 GHz) Micro Rain Radar [see Peters et al. (2005) for a detailed description], a Raman lidar at 532/604 nm, a GPS dual-frequency receiver to retrieve the column-integrated atmospheric water (Sapucci et al. 2007), a field mill, and a surface weather station to measure surface latent and sensible heat fluxes, soil moisture, and temperature. In addition to the main site, two to four other sites instrumented with disdrometers, rain gauges, a GPS receiver, and field mills (variable number) were installed at various distances from the radar. Rawinsondes were routinely released (at least twice a day). During specific intensive observation periods (IOPs), a triangle of rawinsondes in a nearly equilateral arrangement was launched four times a day (0000, 0600, 1200, and 1800 UTC).

Data access and the CHUVA web page. The CHUVA website (http://chuvaproject.cptec.inpe.br) is the primary access to the CHUVA information and data. For each campaign, a specific web page was developed (Fig. 2). These web pages contain a wide variety of information, including the daily weather report, instrument strategy, instrument locations, quick looks of the main events, data reports, cloud pictures, and the Severe Storm Observation System CHUVA (SOS-CHUVA), a geographical information system that utilizes data from the CHUVA project and allows retrospective access to the radar, satellite, and model images, when available. The use of SOS-CHUVA for nowcasting will be discussed in more detail in the "CHUVA outreach" section. The CHUVA dataset has been preprocessed and is available through the CHUVA website. Data can be accessed at different levels. For example, level 0 data from the X-band radar are raw data in ASCII and universal format (UF), level 1 data consist of the attenuation-corrected (Z_H and Z_{DR}) data in ASCII and UF [see Testud et al. (2000) for a detailed description of the attenuation correction], and level 2 data consist of the corrected reflectivity constant altitude plan position indicators (CAPPIs) at various altitude levels. Additional corrections, such as the correction for bias due to a wet radome and the Z_{DR} offset adjustment, are not applied in this dataset. However, instructions and tables are accessible to the users for their own applications. Data for each instrument come with a "readme" file with information about the data and how to manipulate the files. All raw data and several processed data (level 2) are publicly available through the CHUVA website.

In addition, the CHUVA datasets for each campaign include the available operational S-band radar data covering the field campaign region (see Table 1 for a description of additional instrumentation), the GOES and Meteorological Satellite (Meteosat) geostationary satellite images (infrared channels), and all overpasses of the operational environmental low-orbiting satellites carrying passive microwave sensors [channels similar to the TRMM Microwave Imager (TMI)].

FIELD CAMPAIGNS. *Alcantara.* Alcantara was the first CHUVA campaign from 1 to 25 March 2010. In addition to the array of CHUVA instruments, the Alcantara experiment employed the Advanced Microwave Radiometer for Rain Identification [ADMIRARI; see Battaglia et al. (2011) for a detailed description]. The ADMIRARI measurements consist of passive radiances collected at vertical and horizontal polarization at frequencies of 10.7, 21.0, and 36.5 GHz, and one co-staring active radar (MRR). The ADMIRARI was pointed at a fixed 30° elevation angle oriented along a radial directed toward the X-Pol radar located at a range of 7.65 km. Along the line between the X-Pol radar and the ADMIRARI, two additional sites measured rainfall and drop size distributions.

Three distinct weather conditions were observed during the campaign. During the first period (1–9 March) the convection was suppressed with only scattered clouds and sparse rainfall. The second period (10–16 March) was characterized by the beginning of the wet season with isolated local convection and dominant warm-cloud processes. The last period (16–25 March) experienced intense convection with warm and deep (cold cloud/ice phase) convection, with precipitation rates as high as 150 mm h^{-1}; the 99th percentile corresponds to 137 mm h^{-1} (the rain-rate information described in this study was computed using rain gauge tipping buckets integrated over 1-min intervals). The warm rainfall events in Alcantara were associated with the highest concentration of large drops (larger than 4 mm). Battaglia et al. (2011) describe two precipitation events during the campaign in which the 21.0- and 36.5-GHz channels and the MRR were repeatedly saturated with heavy rain. In one event, the 10-GHz signal was saturated, which was the first time the ADMIRARI operation ever observed saturation on this channel (this was the third ADMIRARI campaign). TRMM collocated 2A25 version 7 near–surface precipitation radar was compared against the precipitation measured during the CHUVA campaign by rain gauge. Alcantara precipitation estimation from TRMM is underestimated

Fig. 2. (top middle) The CHUVA web page and (left) examples of the data access panel, and (right) the web page for the Vale do Paraiba campaign. (bottom middle) One example picture showing the radar installation for the Vale do Paraiba campaign is shown.

by more than 50%. Of all the campaigns to date, Alcantara has the highest average rainfall rate from warm clouds (7.2 mm h^{-1}), one of the largest vertically integrated water vapor values, and high cloud water contents for nonprecipitating clouds (0.34 mm), only slightly smaller than observed in Belém. Alcantara also has the highest CAPE; the 99th percentile corresponds to 1950 J kg^{-1}.

Fortaleza. The data collection period spanned 3–28 April 2011, during the rainy season. The main site was installed in the yard of the Civil Defense Organization (the organization responsible for responding to natural disasters) in Fortaleza. A partnership with Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME) was established for monitoring intense thunderstorms. The X-Pol radar was installed in the city of Osorio, 20.5 km from the main CHUVA site. Additionally, three more sites with disdrometers, rain gauges, and GPS receivers were installed around Fortaleza, and the most distant was 32.6 km from the radar. Given that the focus of this campaign was warm-cloud processes and deep convection associated with the intertropical convergence zone (ITCZ), a volume scan strategy was implemented with 13 elevations focusing on both the lower and upper troposphere (i.e., warm and deep cloud types). As already mentioned, the strategy for all campaigns included a Z_{DR} offset check and RHIs scans. For Fortaleza, two RHI scans were performed: one over the main site and another at 180°, perpendicular to the coast, where most systems propagate into the

Table 1. Description of the experiment period, additional instruments, and the radars employed during each campaign, and a description of the instruments at the main site.

Experiment	Period	Additional instruments	Radars
Alcantara	1–25 Mar 2010	ADIMIRARI radiometer	EEC X-band dual-pol
Fortaleza	3–28 Apr 2011	—	Gematronik Meteor 50DX X-Pol
Belém	1–30 Jun 2011	Controlled meteorological balloons and GPS network	Gematronik Meteor 50DX X-Pol and S-band Doppler
Vale do Paraiba	1 Nov 2011–31 Mar 2012	Lightning detection networks and high-speed cameras	Gematronik Meteor 50DX X-Pol and 2 S-band Doppler
Santa Maria	5 Nov–12 Dec 2012	Mesoscale network of automated weather station	IACIT 2 S-band Doppler

Main site

Instruments	Manufacture	Measurement	Retrieval parameter
Microwave radiometer	MP3000A (Radiometrics)	35 microwave brightness temperature channels [22–30 and 51–59; IR channel (9–11 μm)]	Temperature, humidity, water vapor density, and liquid water profiles and integration
Disdrometer	Joss–Valdwogel (RD-80, Disdromet Ltd.) and PARSIVEL (OTT Inc.)	DSD impact (Joss–Valdwogel) and laser (PARSIVEL)	DSD, rain rate, liquid water content, and terminal velocity
Rain gauge	Tipping bucket (Hydrological Services rain gauge 0.01 in. (0.254 mm)	Rainfall	Rain rate
Vertical-pointing radar	Micro Rain Radar (MRR-2), vertical pointing—24.1 GHz (METEK)	Doppler spectral	Reflectivity, rain rate, liquid water content, terminal velocity, and path-integrated attenuation
Lidar	Visible Raman lidar at 532/604 nm (LB10 D-200, Raymetrics)	Backscattering extinction profile	Cloud and aerosol extinction profile and cloud thickness
GPS	Trimble NetR8 Global Navigation Satellite System (GNSS) receptor dual frequency	Zenithal tropospheric delay	Integrated water vapor
Surface tower	Solar Kipp & Zonen instruments, Campbell Scientific and LI-COR, Inc. weather instruments, CS7500, open path analyzer measuring CO_2 and H_2O surface fluxes using eddy covariance technique	Surface weather variables, soil and temperature, radiative budget, and CO_2 and H_2O eddy covariance	Radiative budget, soil temperature and moisture, surface air relative humidity, temperature and wind, moisture, CO_2, and heat fluxes

continent. Three complete scans (volume scan, RHIs, and vertically pointing) were run in 20-min cycles and a zero check (background noise estimation) was performed once per hour.

Rawinsondes were launched in Fortaleza every 6 h. However, in the time interval of 8–17 April, two additional sites located 135 km away in the cities of Quixeramobim and Mossoró were added, and these began to launch rawinsondes concurrently. This nearly equilateral triangular sounding array was designed to cover mesoscale systems penetrating the continent. During this period, multiple organized convective systems crossed the array in succession.

The maximum rainfall intensity recorded during the campaign was 152 mm h^{-1}, with the drop size distributions (DSDs) revealing a large population of large (>4 mm) raindrops. Fortaleza had the largest average vertically integrated water vapor (56.1 mm) and the highest melting level (4.7 km). These characteristics suggest that the rainfall events in Fortaleza appear to have a very important warm process when producing rain drops. Additionally, the stratiform rainfall in Fortaleza exhibited the highest and least prominent brightband (BB) peak intensity (Calheiros and Machado 2014). Fortaleza had the second highest CAPE; the 99th percentile corresponds to 1840 J kg^{-1}.

Belém. The Belém campaigns was performed during the period 1–30 June 2011, toward the end of the wet season and during the period of maximum squall-line frequency [see Garstang et al. (1994) and Cohen et al. (1995) for a detailed description of Amazonian squall lines]. Negri et al. (2000) used a satellite-derived gauge-adjusted precipitation climatology from microwave measurements (i.e., the Goddard profiling algorithm). They found a persistent local rainfall maximum at 1800 LST, which moved inland at 2100 LST, because of interactions between sea breeze and squall-line formation and propagation into the Amazon along the northern coast of Brazil.

The X-Pol radar was installed on the roof of the Meteorology Department of the Federal University of Pará along the Guamá River, a tributary of the Amazon River. Two main sites were set up, one in Outeiro and another in Benevides, 23.0 and 27.7 km from the radar, respectively. In general, rawinsondes were launched twice daily in Belém, with the exception of an intensive observation period from 18 to 26 June, during which four rawinsondes were launched daily in the cities of Tomé Açu and São Miguel, approximately 120 km apart. The radar volume scan strategy was similar to that used in the previous experiments. Additionally, within the 10-min scan period strategy, 10 more RHIs were performed (separated by 1.5°) perpendicular to the Amazon River covering the rawinsondes triangle network. In addition to the typical CHUVA instrumentation, a mesoscale GPS meteorological network was established (Adams et al. 2011) with 15 stations in close proximity (a 5–10-km separation distance within Belém and a 40-km distance outside of Belém). This GPS network provided very high spatial and temporal resolution for the column-integrated atmospheric water vapor and its variability. Additionally, three field mill sensors were installed at Belém and the main sites. Finally, controlled meteorological (CMET) balloons (Voss et al. 2005) were launched from Tomé-Açu, Pará. These balloons are altitude controlled via satellite, and the winds were determined using GPS tracking and a package carrying temperature and moisture sensors. Two CMETs were launched 12 h apart. The CMET measurements (i.e., temperature and relative humidity) show the same boundary layer structure as the Tomé-Açu rawinsondes. Each CMET was recovered. The CMETs landed in the Tocantins River after 6 h of flight. During the flights, a mesoscale convective system to the south led to a strong directional wind shear in the lower layers. Preliminary numerical studies using the BRAMS model employing back trajectory are consistent with a southerly flow in response to a depression associated with the interaction of a mesoscale convective system and a developing sea breeze, which also promoted a southerly flow.

Several squall lines formed along the coast and sea-breeze front, propagating inland over the Amazonian rain forest, as described earlier by Cohen et al. (1995). However, several of the observed squall lines were not initiated along the coast but along the boundary of the rain forest and the semiarid region to the east of Belém. These squall lines propagated almost parallel to the coast. Another interesting feature was the multiscale nature of these large squall lines. Embedded in the large cloud deck, successively smaller-scale propagating rainfall cell lines were detected by the radar. Figure 3 displays one example of the consecutive RHI scans through the squall line on 7 June 2011. A typical vertical cross section of the evolving squall line is apparent; initially shallow warm clouds develop, followed by rapidly deepening clouds up to 14 km. Following the convective region, the stratiform sector evolved with a clear bright band and a cloud top of approximately 13 km at 2200 UTC. During the dissipation phase (cloud collapse), the cloud-top height decreases and the brightband region intensifies. The brightband signature is the result of complex microphysical processes that occur when snowflakes melt in stratiform precipitation (Fabry and Zawadzki 1995). More than 20 rain events crossed the experimental region; the rain rate at the 99th percentile was 122 mm h^{-1}. The CAPE was also very high. However, the CAPE was less than at Alcantara and Fortaleza; the 99th percentile corresponds to 1380 J kg^{-1}.

Vale do Paraíba. The Vale do Paraíba campaign had the longest duration, with an IOP from 1 November to 22 December 2011, followed by a second period with less intensive measurements continuing through 31 March 2012. The instrumentation was installed along a line perpendicular to the coast. The radar was 90 km inland from the ocean at an elevation of 650 m. The main site was installed 11 km from the X-Pol radar, and a succession of sites (spaced by approximately 20 km) was installed along a line perpendicular to the ocean. These sites had at least one GPS integrated precipitable water (IPW) station, one disdrometer, and multiple rain gauges. Additionally, five field mills, spaced 1 km apart, formed a very high-spatial-resolution array close to the radar. The radar strategy was designed to run for 6 min.

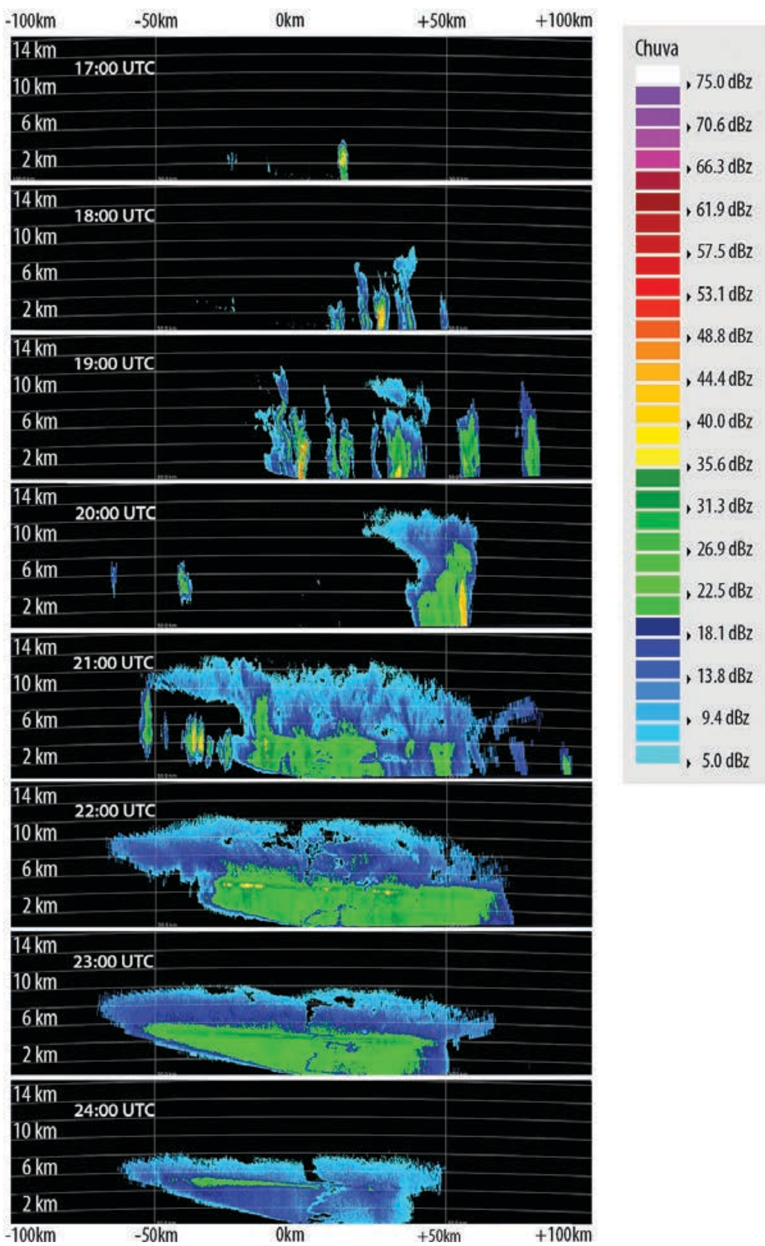

Fig. 3. The sequence of the RHI over a squall line crossing the main site. The illustration is presented for each hour from 1700 to 2400 UTC (7 Jun 2011) for the Belém field campaign.

During November and the first week of December, the region had an anomalous southeasterly flow, decreasing the air temperature and increasing convective inhibition. From the second week of December through March, several intense thunderstorms and some severe weather events were reported in the region.

The primary objective of this campaign was to study storm electrification. As such, comprehensive ground-based measurements of total lightning activity were collected to improve our understanding and knowledge of thunderstorm initiation and behavior and also to develop more advanced nowcasting tools that combine radar, lightning, satellite, and numerical weather prediction (Goodman et al. 2012). The second objective was to conduct cross-network intercomparisons and capability assessments of operational and research ground-based regional 2D and 3D total lightning mapping networks that might be useful for merging with or validating the space-based lightning measurements becoming available late this decade. This specific component of the field experiment included a very successful collaboration among Brazilian, U.S., and European organizations (from universities and industry). The participating lightning location systems (LLSs) were Sferics Timing and Ranging Network (STARNET), Rede Integrada Nacional de Detecção de Descargas Atmosféricas (RINDAT), World Wide Lightning Location

Network (WWLLN), Arrival Time Difference Network (ATDnet), Vaisala Global Lightning Dataset 360 (GLD360) and Total Lightning Sensor (TLS200), Sistema Brasileiro de Detecção de Descargas Atmosféricas (BrasilDAT), Lightning Network (LINET), and Lightning Mapping Array (LMA). The last four networks were deployed along a short baseline for total (intracloud and cloud to ground) lightning detection in support of the development of proxy datasets and validation protocols in preparation for the next generation of operational weather satellites (Goodman et al. 2013) and the Meteosat Third Generation Lightning Imager in 2018 (Höller et al. 2013). The lightning measurements provided by these LLSs were made concurrently with overpasses of the TRMM Lightning Imaging Sensor (LIS) and the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on the Meteosat Second Generation satellite. A 10-station Lightning Mapping Array network, expanded to 12 stations in early December and then providing near-real-time data, was deployed over the eastern region of the Vale do Paraiba in the vicinity of São Paulo to be one of the references for total lightning measurements. The distance between the LMA stations was 15–30 km, and the network "diameter" was approximately 60 km. Bailey et al. (2011) discuss a similar LMA configuration that provides accurate 3D lightning mapping and good detection efficiency as far as 150 km from the network center. This specific network installed in CHUVA has no information about the specific efficiency detection; this information will be available only after the cross-network intercomparisons.

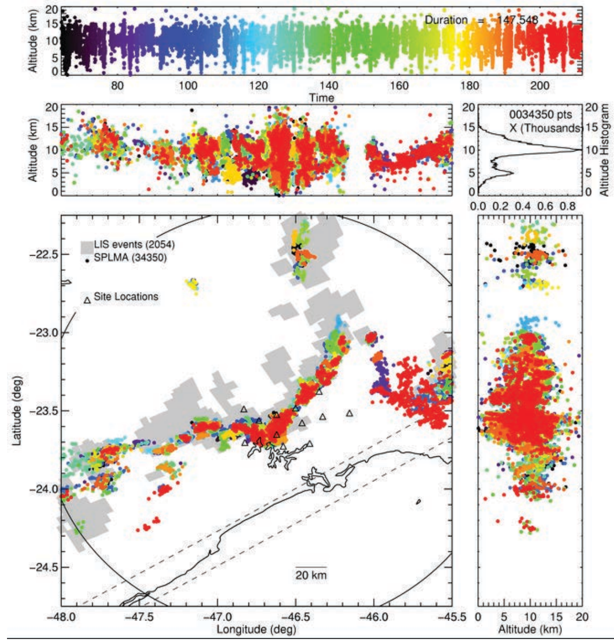

Fig. 4. (top) The coincident lightning observations at 1900 UTC 10 Feb 2012 during an LIS overpass from approximately 1901:10 to 1903:24 UTC. The plotted ground-based lightning data are limited both temporally and spatially to the LIS overpass limits. (bottom left) The LIS pixels (gray squares) and the ground strikes detected by LMA very high frequency (VHF) sources (the colored dots are a function of the time). The projections (middle left) east–west and (bottom right) north–south as functions of the altitude and (middle right) the number of sources as a function of the altitude are also shown.

The combined lightning, satellite, and radar data provide the most comprehensive dataset to date. The dataset prepares users for the next generation of geostationary satellite imagery and lightning mappers using SEVERI and LIS measurements. Figure 4 presents an example of the characteristic lightning data collected during one overpass of the TRMM satellite. The LMA and the LIS were able to detect and locate lightning from various subcomponents of individual flashes.

Additionally, nowcasting applications were tested based on detailed information of intense thunderstorms that produced hail, damaging winds, and flooding over the metropolitan area of São Paulo and Vale do Paraiba. Figure 5 provides an example of a severe weather event that produced very large hail (up to 20 mm) and flooding in the region. A rapid increase in lightning source numbers, known as the "lightning jump," first discussed by Williams et al. (1999), is associated with severe weather, occurred in advance of the hail event. Figure 5a shows the 15-min accumulated LMA source density (number of sources in a 1 × 1 km^2 grid during a 15-min period) plotted in latitude–longitude, latitude–height, and longitude–height projections and the observed signature of the lightning jump. This cell was initiated southwest of Sao Paulo and traveled through Sao Paulo and Guarulhos cities with reflectivities greater than 40 dB*Z* from 1700 to 1830 UTC, reaching values greater than 65 dB*Z* at 1745 UTC when hail was reported in downtown Sao Paulo. Moreover, 15 min later, hail and flooding were reported in Guarulhos, which corresponds with the maximum observed LMA sources (Fig. 5b). The electrical structure of this cell exhibited two well-developed charge centers with maximum activity near 1800 UTC. This lighting source maximum (lightning jump) has been associated with severe weather, including tornadoes (Schultz et al. 2009). The lightning activity had two major source regions at approximately 7 and 10 km. These thunderstorms extended to a height of 18 km. Cloud electrification is tightly controlled by updrafts and precipitation formation. Therefore, monitoring lightning activity inside a cloud can lead to severe weather warnings detected by a lightning-jump signature.

The LMA mapped the convective cells in near–real time. The most recent 10 min of the LMA lightning data were uploaded to the CHUVA nowcasting website (SOS) every 5 min. This site provides civil defense, management organizations, electrical power companies, and the public with information on real-time convection and lightning threat.

During the Vale do Paraiba campaign, several intense thunderstorms and some severe weather events were recorded, including a downburst, causing destruction of many trees, and many cases of hailstorms. The rain rate at the 99th percentile at the main site was 137 mm h^{-1}. Warm clouds during the Vale do Paraiba campaign had a lower frequency and average rain rate than the other CHUVA tropical sites. Moreover, nonprecipitating clouds exhibited a small average cloud integrated liquid water content (0.13 mm) and the largest difference with the adiabatic calculation. One possible reason for this finding is the dry entrainment effect that reduces the liquid water content below the estimated adiabatic value. The CAPE value at Vale do Paraiba was nearly identical to the observations in Belém; the 99th percentile corresponds to 1260 J kg^{-1}. The Vale do Paraiba and Santa Maria locations had smaller average integrated water vapor amount (27 and 29 mm, respectively) compared with the sites located closer to the equator.

Santa Maria. The Santa Maria campaign, named CHUVA SUL, took place from 5 November to 12 December 2012. Zipser et al. (2006) report that very intense thunderstorms are observed in this region and mesoscale convective systems organized by the penetration of cold fronts are common. Liu et al. (2010) used a 10-yr satellite database from TRMM to show that most precipitation in this region (more than 2000 mm yr^{-1}) comes from thunderstorms. During the campaign, the rain rate at

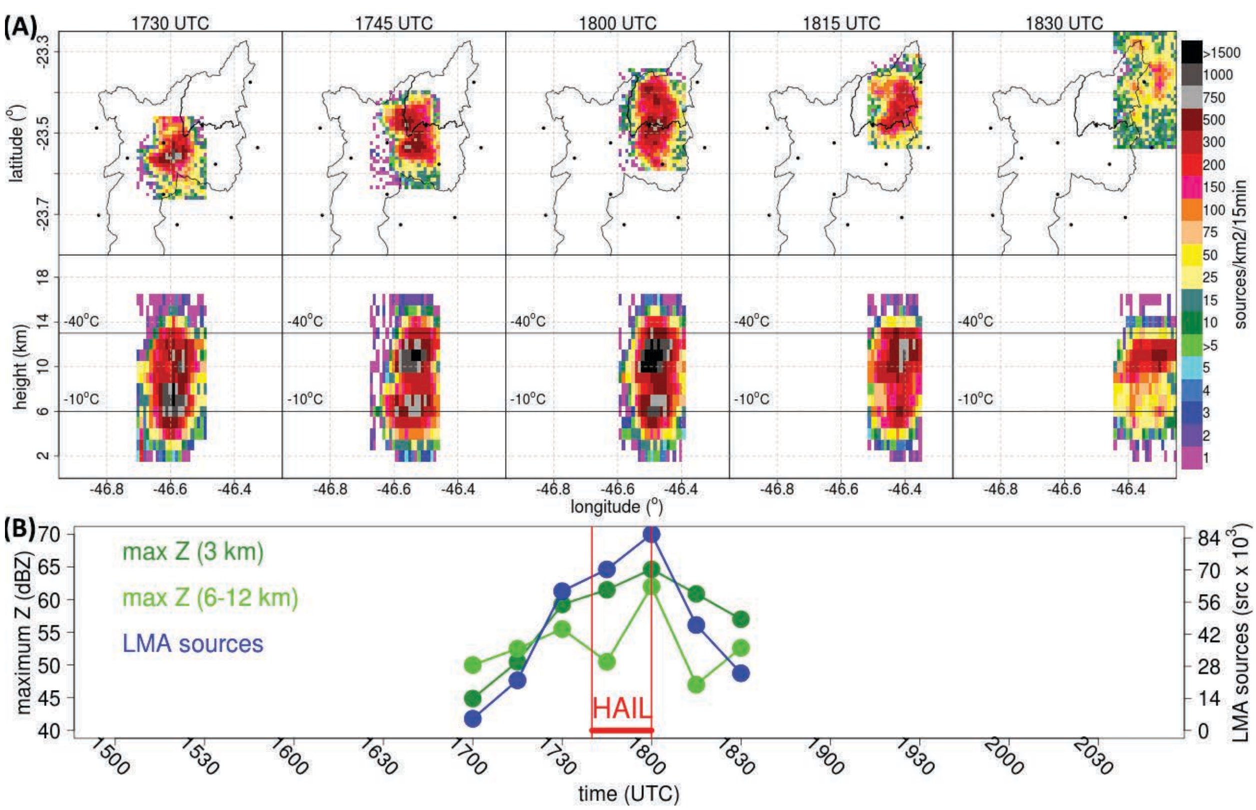

Fig. 5. (a) Accumulated LMA lightning source density (number of sources in a 1 × 1 km^2 grid box during a 15-min period) for a hail-producing convective cell on 7 Jan 2012. (top) A plan (latitude–longitude) view and (bottom) height–longitude views of the convective cell. Horizontal black lines in the bottom panels indicate the approximate heights of the –10° and –40°C isotherms, where most of the electrical charge transfer occurs. (b) Time evolution of the maximum reflectivity and the number of LMA lightning sources. Red lines indicate hail occurrences in São Paulo and Guarulhos [the two cities shown in (a)]. Only data from the hail-producing convective cell are shown.

the 99th percentile was 106 mm h^{-1}. Six mesoscale convective systems crossed the region during the campaign, with intense activity confined primarily to Argentina and Uruguay. On 1 December, a convective event brought down trees near the main site and was considered the most intense storm crossing the sites. Unfortunately, the X-band radar suffered a voltaic arc and could not be repaired in time for the campaign. However, two S-band radars operated by the Brazilian Air Force, one in Santiago and another in Cambuçu, 100 and 180 km from the main site, respectively, made measurements during this event. These radars ran a volume scan strategy, employing 15 elevations every 10 min. All of the CHUVA instruments were installed similar to the other campaigns using rainfall measurement sites, a GPS mesoscale network, and a field mill network. Additional instrumentation included surface weather stations in a mesoscale network composed of six stations spaced 20 km apart. The rawinsondes were launched twice a day. During the occurrence of organized systems, soundings were also launched every 6 h in Santiago and Cruz Alta, approximately 120 km apart. The Santa Maria campaign showed the lowest value for CAPE; the 99th percentile corresponds to only 400 J kg^{-1}, larger values were only observed close to the six main events. A unique activity in CHUVA SUL was the use of the High-Resolution Limited-Area Model Ensemble (HRLAMENS). The HRLAMENS effort was developed under mutual collaboration between CHUVA and the La Plata Basin Research and Development Project (LPB–RDP, which focuses on high-impact weather), which aimed to furnish additional information on the total amounts and locations of precipitation and their uncertainties. The HRLAMENS was composed of five models [two versions of the BRAMS model and three versions of the Weather Research and Forecasting Model (WRF)], which were integrated using the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC) supercomputing facilities. Moreover, four other model configurations were run in other institutions in Brazil and Argentina. This core set of models was designed to be driven by selected global ensemble prediction system members from CPTEC and the National Centers for Environmental Prediction (NCEP). The simulations were homogeneous in domain size and horizontal and vertical resolution (2-km grid spacing and 41 levels). Partner institutions in the project assisted with the multimodel composition in their respective models [WRF running at University of Buenos Aires, WRF running at University of Santa Maria, and Nonhydrostatic Mesoscale (Méso-NH) model from the Laboratoire d'Aerologie (France)]. The results are still being evaluated. Nevertheless, preliminary conclusions indicate, as expected, sensitivity to the lateral boundary conditions and model characteristics. The ultimate objective is to find an optimal balance among ensemble members that would improve the current state of rainfall predictions for the region.

GoAmazon—Manaus. The GoAmazon experiment seeks to understand the interaction of aerosol and cloud life cycles. The GoAmazon experiment will be performed in Manaus, a megacity of almost 1.8 million people in the central Amazon. Two IOPs are being prepared for 2014, one in February–March, during the wet season, and another in September–October, at the end of the dry season. The GoAmazon experiment consists of several combined efforts, including the deployment of the Atmospheric Radiation Measurement Program (ARM) mobile facility (Cadeddu et al. 2013); the Grumman Gulfstream 159 (G-1) aircraft (from the Pacific Northwest National Laboratory) to collect chemistry and microphysical properties; Aerosol, Cloud, Precipitation, and Radiation Interactions and Dynamics of Convective Cloud Systems (ACRIDICON) with the High-Altitude and Long-Range Research Aircraft (HALO), which is the new research aircraft of the German Science Community (Gulfstream G-550); and the CHUVA project. The CHUVA campaign will employ an X-Pol measurement strategy that provides volume scans and several RHIs over the sites in coordination with the ARM cloud radar. It is important to note that the GPM core observatory will be launched during the first IOP. Hence, there will be an opportunity to combine data from the TRMM and GPM core satellites with those collected during GoAmazon to study cloud and precipitation processes over one of the rainiest continental regions of the planet.

CHUVA OUTREACH. *The SOS-CHUVA nowcasting system.* The SOS-CHUVA is a web-based geographic information system combining observations from radar, lightning networks, satellite images, numerical models, and nowcasting procedures. This is a useful tool to interpret, summarize, and integrate the environmental information and display and send warnings for emergency management groups. In addition, SOS-CHUVA is an open access system serving the population through real-time information, thereby reducing citizen vulnerability. By taking advantage of the instrumentation employed in each campaign, a nowcasting pilot project is set up for each region that addresses specific vulnerabilities and needs. The

SOS-CHUVA provides high-resolution radar, satellite, and lightning data nearly in real time. It also provides the results from several nowcasting applications, including the radar forecast for the next 10 min [based on Fortracc, Vila et al. (2008), and the Rainbow data processing system software] and the lightning probability (Machado et al. 2009), among several other functions, such as the total integrated precipitation for each neighborhood. For the regions outside of the radar coverage, the system provides information based on the hydroestimator and the Fortracc nowcasting cloud systems for the following 2 h using geostationary satellite data. The system also provides forecast data from the BRAMS cloud-resolving model at a resolution of a few kilometers. The SOS-CHUVA in each campaign was developed in partnership with the local civil defense and fire departments.

Training and education and workshop. Outreach activities are an important component of the CHUVA project. For example, training lectures were presented to local students during each campaign via a 1-week course that covered themes of nowcasting, cloud-resolving models, polarimetric radar, satellite data usage, lidar, GPS, and cloud microphysics. The lectures were offered to graduate and undergraduate students in environmental sciences; more than 100 students attended each campaign course. The programs and details of each course are available from the specific web page of the campaign.

Finally, an international workshop was organized in May 2013 in São Paulo. Access to the abstracts and the presentations is available at the following URL: http://chuvaproject.cptec.inpe.br/portal/workshop/index.html.

DISCUSSION. The use of similar instruments across campaigns in the various precipitation regimes makes it possible to study the regional contrasts and correspondences. Figure 6 illustrates examples of similarities and differences among the various precipitation regimes. Figure 6a shows the DSD adjustment to the gamma function [using the momentum method described by Tokay and Short (1996)] in the three-dimensional space of the gamma parameters: the intercept (N_0) in the x axis, the shape (m) in the y axis, and the width (Λ) in the z axis, using the same procedure employed by Cecchini et al. (2014). In this three-dimensional space (a logarithmic option is applied to N_0 to adjust the data to the same range), the DSD gamma parameters are represented for the Vale do Paraiba, Belém, and Santa Maria campaigns.

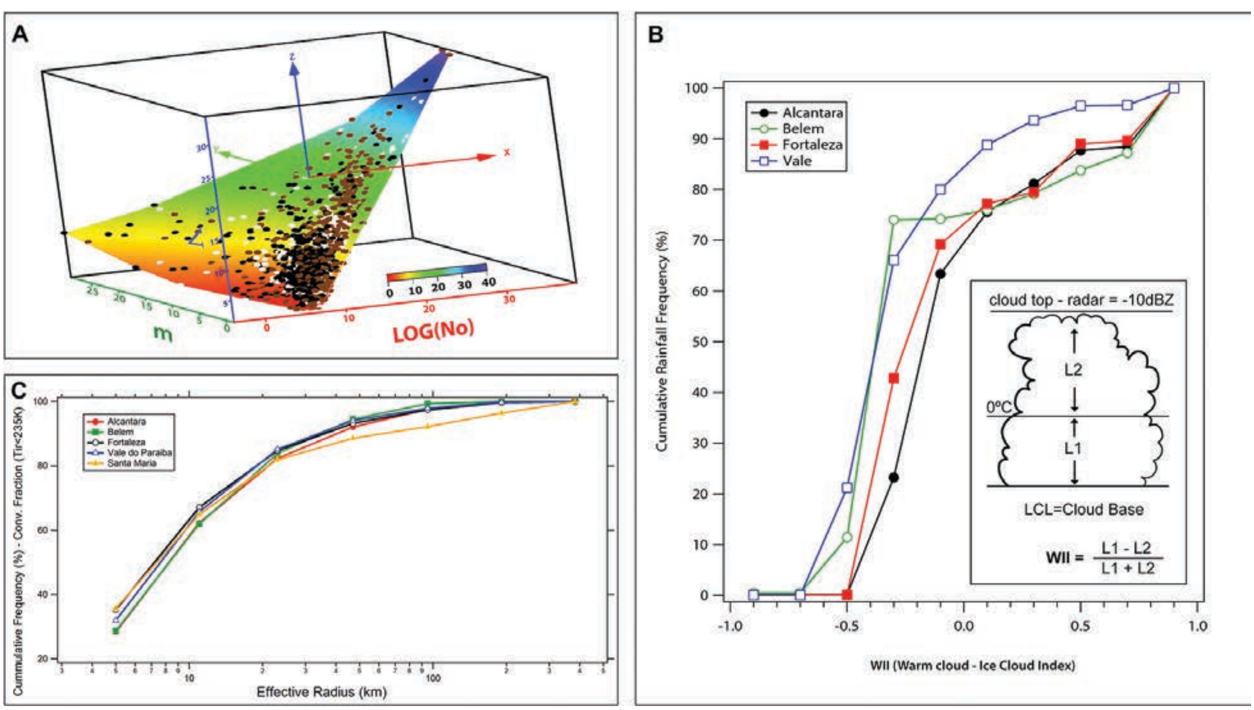

Fig. 6. (a) The DSD gamma parameters for Vale do Paraiba (black dots), Belém (brown dots), and Santa Maria (white dots) in the three-dimensional space composed by N_0, m, and Λ. The color of the interpolated surface is associated with the Λ values. (b) The cumulative rainfall as a function of WII for Alcantara, Fortaleza, Belém, and Vale do Paraiba. (c) The cumulative convective cloud cover (T_{IR} < 235 K) as a function of the cloud-cluster effective radius for each campaign.

Each point in this diagram corresponds to a specific DSD. We note the regional differences in the frequency of occurrence over the gamma parameter's spatial domains. However, it is very interesting to see that all points, regardless of the regime, are nearly over the same adjusted surface. Therefore, we can parameterize the gamma distribution using only two independent parameters. The raindrop size distribution characteristics observed by surface-based disdrometers can distinguish different precipitation systems. Tokay et al. (2002) demonstrated the presence of more large drops and small concentration in the easterly regime than in the westerly regime in the southwestern Amazon Basin. In their study, DSD differences were also observed between the monsoon and break regimes in northwestern Australia. The DSD features from CHUVA will be analyzed in detail after the completion of the GoAmazon project.

Another example of regional contrasts and similarities is presented in Fig. 6b using the warm cloud–ice cloud index (WII). The WII is defined as the ratio of the difference between the cloud thickness of the cloud layer below and above the freezing level and the total cloud thickness (see Fig. 6b for a schematic view and the associated equation). The WII was computed using the vertical profile of reflectivity (VPR) by employing data from the X-Pol RHI scanning mode and the collocated rawinsondes (±3-h interval) over the main site. Only continuous cloud layers were considered in this analysis; multilayer clouds were discarded. A continuous layer cloud was defined as having a continuous layer with values larger than 0 dBZ in the warm sector and –10 dBZ in the layer above the 0°C isotherm. Different thresholds were used because ice has a smaller refractive index than liquid water. All rain events (rain rate greater than 0.1 mm h^{-1}) from nonmultilayer clouds and when rawinsonde data were available were computed in the WII analysis. The thickness of the layer under the melting layer (L1) was defined as the layer between the lifting condensation level (LCL) and the melting level (both obtained from rawinsondes). The LCL is used to avoid possible rain layers detected by the radar below the cloud base. The parameter L2, characterizing the layer above the melting layer, is defined as the thickness of the layer between the melting level and the last level of the continuous layer of reflectivities larger than –10 dBZ. L2 roughly represent the cloud layer above the 0°C isotherm because radar does not detect the cloud boundaries. The WII ranges from 1 (a pure warm cloud) to –1 (clouds associated only with ice and/or supercooled water). Figure 6b presents the rainfall cumulative frequency for each WII value. The cumulative rainfall is obtained from a disdrometer located at the main site along the RHI azimuth direction employed to build the VPR. The population for each site (rainfall cases at the main site were associated with a single layer cloud that occurred within the 6-h interval centered on the rawinsonde launch time) is variable, ranging from 116 in Alcantara to 1500 in Vale do Paraiba, depending on the number of rainy days, the frequency of multilayer clouds, and the duration of the campaign. The cumulative rainfall, for each site, is presented as function of the WII values in Fig. 6b to give information about the specific cloud population of WII values in the total rainfall. Two different behaviors can be observed in Fig. 6b.The first behavior corresponds to negative WII values, responsible for approximately 70%–75% of the total precipitation amount. Vale do Paraiba and Belém exhibit deep clouds with a layer L2 above the melting level that is nearly 3 times larger (a WII value of approximately –0.5) than the warm layer L1; for Fortaleza and Alcantara, this layer is only 1.5 times larger than the warm layer (a WII around –0.3). The second behavior, accounting for the remaining 30%–25% of precipitation, is nearly linearly distributed for the positive values of the WII, except for Vale do Paraiba. These clouds are characterized by rain processes that are primarily below the melting layer. Alcantara, Belém, and Fortaleza present a very similar behavior; approximately 25% of the precipitation is from clouds with most of their thickness below the melting layer (associated with warm processes). However, the Vale do Paraiba rainfall events display a different behavior, in which a very small portion (i.e., less than 5%) of the rainfall is associated with warm clouds. This clearly shows a distinction between coastal and continental rainfall events; a different population of rainfall events from warm clouds was observed. This difference could be the reason for the cloud process in the clean maritime air near the coast and the more polluted air inland.

Another regional comparison was performed to evaluate cloud organization using GOES images. Figure 6c shows the cumulative distribution of the convective cloud fraction (defined as 10.7-μm brightness temperature smaller than 235 K) as a function of the cloud-cluster effective radius [an equivalent area circle; effective radius = (area/π)$^{1/2}$]. This convective cloud size distribution only includes clouds with very high cloud tops (i.e., colder than 235 K). Therefore, no warm clouds are included. The calculation was performed using the same procedure as employed by Machado and Rossow (1993) over a region centered on the main site with a radius of 250 km. The regional convective cloud size distributions are very similar. Approximately 80% of the convective cloud fraction is explained by cloud organization with radii smaller than 31 km for all regions. Only slight regional differences are noted for convective cloud organization smaller than 31 km effective radius. Alcantara and Belém have fewer small convective clouds than the other sites. Moreover, Vale do Paraiba exhibits more moderately sized systems (approximately 31 km). However, the largest difference is for convective cloud organization larger than 31 km. Santa Maria has the largest cloud organization, probably due to the more baroclinic instability favoring large MCCs and cold fronts.

The CHUVA dataset has just begun to be explored, but some clear regional characteristics can already be described. The warm clouds in Alcantara feature very large droplets (disdrometer measurement) and high liquid water content (microwave radiometer). Several pixels that were classified as stratiform due to the presence of a bright band exhibiting large reflectivities and rain-rate values. It is possible that the ice aloft, prior to the brightband formation, is sufficiently vigorous to produce larger rain rates than expected for normal stratiform cloud conditions. The largest CAPE found in Alcantara could explain this strength in the ice production. The highest and most prominent bright band was observed in Alcantara, which agrees with this notion. Deep convective clouds in Fortaleza display the largest amount of rainwater below the melting layer. Costa et al. (2000) showed different DSDs for maritime, coastal, continental, and polluted warm clouds in the Fortaleza region. They demonstrated a pronounced increase in concentration and a decrease in the maximum droplet diameter as the clouds moved from the ocean to the continent into polluted regions. The high CAPE for these coastal sites helps the development of deep convection. However, these coastal tropical sites have more warm-rain clouds and less deep convection than the Vale do Paraiba and Santa Maria locations. Several processes must be considered, such as the small concentration of cloud condensation nuclei (CCN) at the coastal sites. Moreover, the larger trade wind inversion could contribute suppressing deep convection and increase warm-cloud formation.

The deepest clouds were recorded in Santa Maria, Belém, and Vale do Paraiba. These are the regions of very deep clouds, often with cloud tops above 15 km, and organized convection with a more dominant ice phase. Belém presented the most developed glaciated layer (above 7 km), whereas Vale do Paraiba displayed the most developed mixed-phase layer, That is, between the melting layer and 7 km (Calheiros and Machado 2014).

SUMMARY. CHUVA provides a comprehensive dataset characterizing the main precipitation regimes in Brazil. The project consistently uses a core complement of instrumentation for each campaign and has recorded and made available high-spatial-resolution and high-temporal-resolution observations (ground and satellite based) of cloud and precipitation characteristics.

CHUVA field campaigns around the tropical region of Brazil provide education and training with respect to the employed instrumentation and the physical processes describing cloud and rainfall formation. CHUVA takes advantage of the instrumentation to present a nowcasting testbed based on SOS-CHUVA. CHUVA data are available through the website, which include all of the information on each campaign, daily reports, data strategy, quick looks, instrument locations, and photos.

The CHUVA project contributes to the GLM effort to develop algorithms based on the planned GOES-R and Meteosat third-generation lightning sensors and the preparation of the GPM validation and algorithm development. The large number of warm-rain clouds measured in various regions is an important resource for the satellite precipitation algorithms, especially for GPM, to test the ability of retrieving rainfall from non-ice-scattering clouds over land.

Open access to the database will certainly contribute to improving the knowledge of clouds over tropical regions and advance the description and parameterization of cloud processes.

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REFERENCES

Adams, D. K., and Coauthors, 2011: A dense GNSS meteorological network for observing deep convection in the Amazon. *Atmos. Sci. Lett.,* **12,** 207–212, doi:10.1002/asl.312.

Bailey, J. C., L. D. Carey, R. J. Blakeslee, S. J. Goodman, R. I. Albrecht, C. A. Morales, and O. Pinto Jr., 2011: São Paulo Lightning Mapping Array (SP-LMA): Deployment and plans. *Proc. 14th Int. Conf. on Atmospheric Electricity,* Rio de Janeiro, Brazil, International Commission on Atmospheric Electricity. [Available online at www.icae2011.net.br/index.pt.html.]

Battaglia, A., P. Saavedra, C. A. Morales, and C. Simmer, 2011: Understanding three-dimensional effects in polarized observations with the ground-based ADMIRARI radiometer during the CHUVA campaign. *J. Geophys. Res.,* **116,** D09204, doi:10.1029/2010JD015335.

Berg, W., T. L'Ecuyer, and C. Kummerow, 2006: Rainfall climate regimes: The relationship of regional TRMM rainfall biases to the environment. *J. Appl. Meteor. Climatol.,* **45,** 434–454, doi:10.1175/JAM2331.1.

Cadeddu, M. P., J. C. Liljegren, and D. D. Turner, 2013: The Atmospheric Radiation Measurement (ARM) program network of microwave radiometers: Instrumentation, data, and retrievals. *Atmos. Meas. Tech. Discuss.,* **6,** 3723–3763, doi:10.5194/amtd-6-3723-2013.

Calheiros, A. J. P., and L. A. T. Machado, 2014: Cloud and rain liquid water statistics in the CHUVA campaign. *Atmos. Res.,* **144,** 126–140, doi:10.1016/j.atmosres.2014.03.006.

Cecchini, M. A., L.A.T. Machado, and P. Artaxo, 2014: Droplet size distributions as a function of rainy system type and cloud condensation nuclei concentrations. *Atmos. Res.,* **143,** 301–312, doi:10.1016/j.atmosres.2014.02.022.

Cecil, D. J., and C. B. Blankenship, 2012: Toward a global climatology of severe hailstorms as estimated by satellite passive microwave imagers. *J. Climate,* **25,** 687–703, doi:10.1175/JCLI-D-11-00130.1.

Cohen, J. C. P., M. A. F. da Silva Dias, and C. A. Nobre, 1995: Environmental conditions associated with Amazonian squall lines: A case study. *Mon. Wea. Rev.,* **123,** 3163–3174, doi:10.1175/1520-0493(1995)1232.0.CO;2.

Costa, A. A., C. J. de Oliveira, J. C. P. de Oliveira, and A. J. C. Sampaio, 2000: Microphysical observations of warm cumulus clouds in Ceará, Brazil. *Atmos. Res.,* **54,** 167–199, doi:10.1016/S0169-8095(00)00045-4.

Cotton, W. R., 1982: Modification of precipitation from warm clouds—A review. *Bull. Amer. Meteor. Soc.,* **63,** 146–160, doi:10.1175/1520-0477(1982)0632.0.CO;2.

Fabry, F., and I. Zawadzki, 1995: Long-term radar observations of the melting layer of precipitation and their interpretation. *J. Atmos. Sci.,* **52,** 838–851, doi:10.1175/1520-0469(1995)0522.0.CO;2.

Garreaud, R. D., 2000: Cold air incursions over subtropical South America: Mean structure and dynamics. *Mon. Wea. Rev.,* **128,** 2544–2559, doi:10.1175/1520-0493(2000)1282.0.CO;2.

Garstang, M., H. L. Massie, J. Halverson, S. Greco, and J. Scala, 1994: Amazon coastal squall lines. Part I: Structure and kinematics. *Mon. Wea. Rev.,* **122,** 608–622, doi:10.1175/1520-0493(1994)1222.0.CO;2.

Goodman, S. J., and Coauthors, 2012: The GOES-R Proving Ground: Accelerating user readiness for the Next Generation Geostationary Environmental Satellite System. *Bull. Amer. Meteor. Soc.,* **93,** 1029–1040, doi:10.1175/BAMS-D-11-00175.1.

——, and Coauthors, 2013: The GOES-R Geostationary Lightning Mapper (GLM). *Atmos. Res.,* **125–126,** 34–49, doi:10.1016/j.atmosres.2013.01.006.

Höller, H., H.-D. Betz, C. A. Morales, R. Blakeslee, J. C. Bailey, and R. I. Albrecht, 2013: Multi-sensor field studies of lightning and implications for MTG-LI. *Extended Abstracts, 2013 EUMETSAT Meteorological Satellite Conf. and 19th Satellite Meteorology, Oceanography, and Climatology Conf.,* Vienna, Austria, EUMETSAT and Amer. Meteor. Soc.. [Available online at http://elib.dlr.de/85861/.]

Kouadio Y. K., J. Servain, L. A. T. Machado, and C. A. D. Lentini, 2012: Heavy rainfall episodes in the eastern Northeast Brazil linked to large-scale ocean–atmosphere conditions in the tropical Atlantic. *Adv. Meteor.,* **2012,** 369567, doi:10.1155/2012/369567.

Liu, C., and E. J. Zipser, 2009: "Warm rain" in the tropics: Seasonal and regional distributions based on 9 yr of TRMM data. *J. Climate,* **22,** 767–779, doi:10.1175/2008JCLI2641.1.

——, E. R. Williams, E. J. Zipser, and G. Burns, 2010: Diurnal variations of global thunderstorms and electrified shower clouds and their contribution to the global electrical circuit. *J. Atmos. Sci.,* **67,** 309–323, doi:10.1175/2009JAS3248.1.

Machado, L. A. T., and W. B. Rossow, 1993: Structural characteristics and radiative properties of tropical cloud clusters. *Mon. Wea. Rev.,* **121,** 3234–3260, doi:10.1175/1520-0493(1993)1212.0.CO;2.

——, H. Laurent, and A. A. Lima, 2002: Diurnal march of the convection observed during TRMM-WETAMC/LBA. *J. Geophys. Res.,* **107**(D20), 8064, doi:10.1029/2001JD000338.

——, W. F. S. Lima, O. Pinto Jr., and C. A. Morales, 2009: Relationship between cloud-to-ground discharge and penetrative clouds: A multi-channel satellite application. *Atmos. Res.,* **93,** 304–309, doi:10.1016/j.atmosres.2008.10.003.

Morrison, H., and W. W. Grabowski, 2007: Comparison of bulk and bin warm-rain microphysics models using a kinematic framework. *J. Atmos. Sci.,* **64,** 2839–2861, doi:10.1175/JAS3980.

Negri, A. J., E. N. Anagnostou, and R. F. Adler, 2000: A 10-yr climatology of Amazonian rainfall derived from passive microwave satellite observations. *J. Appl. Meteor.,* **39,** 42–56, doi:10.1175/1520-0450(2000)0392.0.CO;2.

Negri, R. G., L. A. T. Machado, S. English, and M. Forsythe, 2014: Combining cloud-resolving model with satellite for cloud process model simulation validation. *J. Appl. Meteor. Climatol.,* **53,** 521–533, doi:10.1175/JAMC-D-12-0178.1.

Peters, G., B. Fischer, H. Münster, M. Clemens, and A. Wagner, 2005: Profiles of raindrop size distributions as retrieved by microrain radars. *J. Appl. Meteor.,* **44,** 1930–1949, doi:10.1175/JAM2316.1.

Rickenbach, T. M., 2004: Nocturnal cloud systems and the diurnal variation of clouds and rainfall in southwestern Amazonia. *Mon. Wea. Rev.,* **132,** 1201–1219, doi:10.1175/1520-0493(2004)1322.0.CO;2.

Salio, P., M. Nicolini, and E. J. Zipser, 2007: Mesoscale convective systems over southeastern South America and their relationship with the South American low-level jet. *Mon. Wea. Rev.,* **135,** 1290–1309, doi:10.1175/MWR3305.1.

Sapucci, L. F., L. A. T. Machado, J. F. G. Monico, and A. Plana-Fattori, 2007: Intercomparison of integrated water vapor estimates from multisensors in the Amazonian region. *J. Atmos. Oceanic Technol.,* **24,** 1880–1894, doi:10.1175/JTECH2090.1.

Schneebeli, M., J. Sakuragi, T. Biscaro, C. F. de Angelis, I. Carvalho da Costa, C. A. Morales, L. Baldini, and L. A. T. Machado, 2012: Polarimetric X-band weather radar measurements in the tropics: Radome and rain attenuation correction. *Atmos. Meas. Tech.,* **5,** 2183–2199, doi:10.5194/amt-5-2183-2012.

Schultz, C. J., W. A. Petersen, and L. D. Carey, 2009: Preliminary development and evaluation of lightning jump algorithms for the real-time detection of severe weather. *J. Appl. Meteor. Climatol.,* **48,** 2543–2563, doi:10.1175/2009JAMC2237.1.

Schumacher, C., and R. A. Houze, 2003: Stratiform rain in the tropics as seen by the TRMM Precipitation Radar. *J. Climate,* **16,** 1739–1756, doi:10.1175/1520-0442(2003)0162.0.CO;2.

Silva Dias, M. A. F., Ed., 2009: As chuvas de novembro de 2008 em Santa Catarina: Um estudo de caso visando à melhoria do monitoramento e da previsão de eventos extremos. Tech. Note, São José dos Campos, INPE, 67 pp. [Available online at www.ciram.com.br/ciram_arquivos/arquivos/gtc/downloads/NotaTecnica_SC.pdf.]

Tapiador, F. J., and Coauthors, 2012: Global precipitation measurement: Methods, datasets and applications. *Atmos. Res.,* **104–105,** 70–97, doi:10.1016/j.atmosres.2011.10.021.

Testud, J., E. Le Bouar, E. Obligis, and M. Ali-Mehenni, 2000: The rain profiling algorithm applied to polarimetric weather radar. *J. Atmos. Oceanic Technol.,* **17,** 332–356, doi:10.1175/1520-0426(2000)0172.0.CO;2.

Tokay, A., and D. A. Short, 1996: Evidence from tropical raindrop spectra of the origin of rain from stratiform versus convective clouds. *J. Appl. Meteor.,* **35,** 355–371, doi:10.1175/1520-0450(1996)0352.0.CO;2.

——, A. Kruger, W. Krajewski, and A. Perreira, 2002: Measurements of drop size distribution in southwestern Amazon region. *J. Geophys. Res.,* **107,** 8052, doi:10.1029/2001JD000355.

Vila, D. A., L. A. T. Machado, H. Laurent, and I. Velasco, 2008: Forecast and Tracking the Evolution of Cloud Clusters (ForTraCC) using satellite infrared imagery: Methodology and validation. *Wea. Forecasting,* **23,** 233–245, doi:10.1175/2007WAF2006121.1.

Voss, P. B., E. E. Riddle, and M. S. Smith, 2005: Altitude control of long-duration balloons. *J. Aircr.,* **42,** 478–482, doi:10.2514/1.7481.

Ware, R., R. Carpenter, J. Güldner, J. Liljegren, T. Nehrkorn, F. Solheim, and F. Vandenberghe, 2003: A multichannel radiometric profiler of temperature, humidity, and cloud liquid. *Radio Sci.,* **38,** 8079, doi:10.1029/2002RS002856.

Williams, E. R., and S. B. Stanfill, 2002: The physical origin of the land–ocean contrast in lightning activity. *C. R. Phys.,* **3,** 1277–1292, doi:10.1016/S1631-0705(02)01407-X.

——, and Coauthors, 1999: The behavior of total lightning activity in severe Florida thunderstorms. *Atmos. Res.,* **51,** 245–265, doi:10.1016/S0169-8095(99)00011-3.

Zipser, E. J., C. Liu, D. J. Cecil, S. W. Nesbitt, and D. P. Yorty, 2006: Where are the most intense thunderstorms on Earth? *Bull. Amer. Meteor. Soc.,* **87,** 1057–1071, doi:10.1175/BAMS-87-8-1057.

NORTH ATLANTIC TROPICAL CYCLONES AND U.S. FLOODING

BY GABRIELE VILLARINI, RADOSLAW GOSKA, JAMES A. SMITH, AND GABRIEL A. VECCHI

North Atlantic tropical cyclones are responsible for major flooding over large areas of the continental United States.

Over the past few years, we have been witnessing growing media coverage for inland flooding associated with North Atlantic tropical cyclones (TCs), with Hurricanes Irene (2011), Isaac (2012), and Sandy (2012) representing the "poster children" of this heightened interest. Flooding associated with landfalling TCs claims a large economic and societal toll, with several billion dollars in damage and numerous fatalities (e.g., Rappaport 2000; Pielke et al. 2008; Changnon 2008; Czajkowski et al. 2013; Jonkman et al. 2009; Mendelsohn et al. 2012; Peduzzi et al. 2012). As summarized by an article in the *New York Times* ("Storm's push north leaves punishing inland flooding," 30 August 2011) about Hurricane Irene (2011), "While most eyes warily watched the shoreline during Hurricane Irene's grinding ride up the East Coast, it was inland—sometimes hundreds of miles inland—where the most serious damage actually occurred. And the major culprit was not wind, but water." In fact, flooding does not only impact the coastal regions close to the point of landfall, but also affects large areas away from the coast, and often hundreds of kilometers away from the center of the storm (e.g., Villarini et al. 2011). Despite these large societal and economic repercussions, there is limited published literature about inland flooding from TCs, in contrast to the attention that has been paid in monitoring and improving the understanding of coastal damage caused by storm surge and wind (e.g., Elsberry 2002; U.S. Department of Commerce 2011; Zandbergen 2009).

While various studies have examined heavy rainfall associated with North Atlantic TCs (e.g., Groisman et al. 2004; Larson et al. 2005; Shepherd et al. 2007; Knight and Davis 2009; Konrad and Perry 2010; Kunkel et al. 2010; Barlow 2011), the little attention that inland TC flooding has received has generally focused on case studies of specific events or over a specific area (e.g., Sturdevant-Rees et al. 2001; Smith et al. 2011; Villarini et al. 2011; Villarini and Smith 2010, 2013). Heavy rainfall is an important ingredient in flood generation, yet it is insufficient to allow direct inference of flooding because of the crucial role of localized differences in land use/land cover and antecedent soil moisture conditions in

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flooding (e.g., Hellin et al. 1999; Sturdevant-Rees et al. 2001). In this study we produce a climatology of flooding associated with North Atlantic TCs, highlighting the regions of the United States for which these storms are important flood agents. The focus will be on all the TCs making landfall in the United States from 1981 to 2011, and the methodology will leverage on U.S. Geological Survey (USGS) discharge measurements to provide a data-driven climatological view of flooding associated with these catastrophic events.

Moreover, while there is a growing literature examining the relationship between TC frequency and large-scale climate predictors (e.g., Elsner et al. 2000; Camargo et al. 2007; Latif et al. 2007; Vimont and Kossin 2007; Vecchi and Soden 2007; Tippett et al. 2011; Villarini et al. 2010, 2012), the nexus between magnitude and frequency of flooding associated with TCs and climate controls is still unexplored. Here we will examine the controls exerted by the North Atlantic Oscillation (NAO) and El Niño–Southern Oscillation (ENSO) on TC flood magnitude and frequency because of their link with U.S. landfalling TCs (e.g., Bove et al. 1998; Elsner et al. 2000, 2004; Elsner 2003; Pielke 2009; Kossin et al. 2010; Colbert and Soden 2012; Villarini et al. 2012).

METHODOLOGY. We examine U.S. flooding associated with landfalling TCs over the period 1981–2011 using the discharge measurements from 3090 USGS stream gage stations (consult supplementary Fig. ES1 online at http://dx.doi.org/10.1175/BAMS-D-13-00060.2 for their location and data availability). We define as the flooding associated with a TC the largest flood peak measured by a stream gage station located within 500 km from the center of the storm during a time window of two days prior to and seven days after the passage of a storm (e.g., Hart and Evans 2001; Kunkel et al. 2010; Barlow 2011; Villarini and Smith 2010, 2013). At each stream gage station, we then compute the 10-yr flood peak, which represents the flood peak that is expected to occur, on average, once every 10 years and corresponds to the 90th percentile of the flood peak distribution. We focus on stations with at least 20 annual maximum flood peaks over the period 1981–2011 (they represent the largest flood peak in a given year) and compute the 90th percentile of the flood peak distribution at each location. The 10-yr flood peaks are computed only over the past 31 years to mitigate potential effects due to anthropogenic modifications of these catchments (e.g., construction of dams, changes in land use/land cover; e.g., Villarini and Smith 2010, 2013).

Because of the strong link between discharge and drainage area (i.e., watersheds with larger drainage area will tend to have larger discharge values; e.g., Gupta et al. 1994), we need to normalize the TC flood peaks by their 10-yr flood peak to be able to provide a regional view. This flood ratio provides information about how much larger than the 10-yr flood peak the TC flood was: values larger (smaller) than 1 indicate that flood peaks caused by a given TC are larger (smaller) than the 10-yr flood peak. Recently, Rowe and Villarini (2013) used this approach to characterize flooding associated with six predecessor rain events over the central United States.

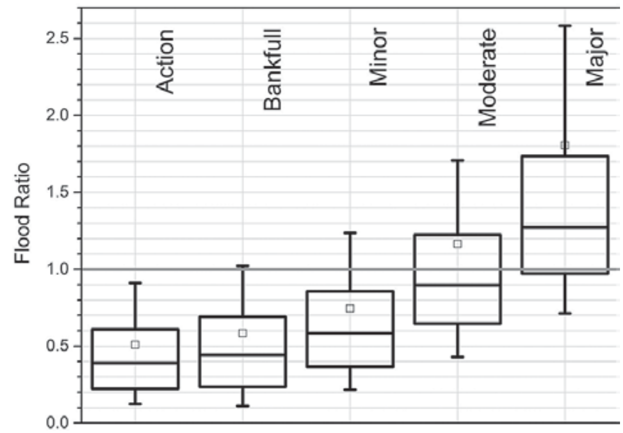

Fig. 1. Relationship between the values of the flood ratios and NWS high water terms. The whiskers represent the 10th and the 90th percentiles, the limits of the boxes the 25th and 75th percentiles, and the horizontal line and square inside the boxes the median and mean, respectively.

To place the flood ratio values in context, we use the high water level terminology of the National Weather Service (NWS). There are three main high water terms used by NWS: "action," "bankfull," and "flood." The flood term is further divided into minor, moderate, and major. A definition of each of these terms is provided by NWS (2012). For a given stream gage station, we can compute the flood ratio value corresponding to each of the NWS high water terms. We can do this for all of the 3090 USGS stations for which a NWS classification is in place, and plot the distribution of the flood ratio values corresponding to each category (Fig. 1). By using the median as reference point, flood ratios between 0.5 and 0.6 refer to bankfull conditions (the distribution and values for the action level are similar but slightly smaller), with values larger than 0.6 referring to flooding. Between 0.6 and 1, the flood ratio generally indicates minor to moderate flooding, with values in excess of 1–1.3 pointing to major flooding. Keeping in mind the variability within each category, these results are helpful in interpreting the values of the

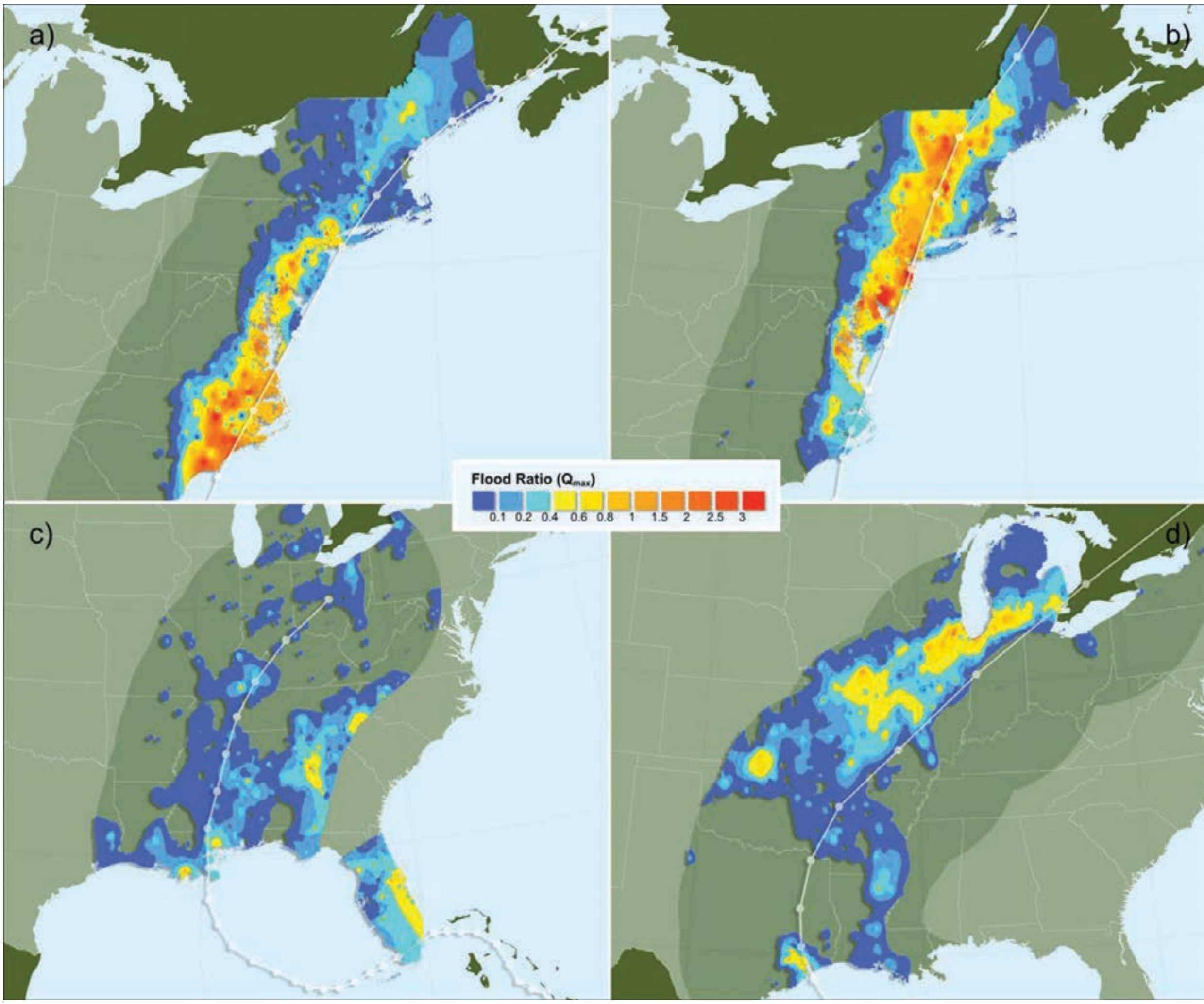

Fig. 2. Flood ratio maps for (a) Hurricane Floyd (1999), (b) Hurricane Irene (2011), (c) Hurricane Katrina (2005), and (d) Hurricane Ike (2008). Values larger (smaller) than 1 indicate TC flood peaks larger (smaller) than the 10-yr flood peak at a particular location (see Fig. 1 for NWS high water classification). Each storm track is displayed in white [from the North Atlantic Hurricane Database (HURDAT)]. The darker shades of green represent the 500-km buffer around the center of circulation.

flood ratio associated with TC flooding in terms of impacts.

The examination of the relationship between TC flooding and large-scale climate indices is based on the stratification of the study period into different groups of years according to the value of the NAO and ENSO. To examine the connection with NAO, we have focused on positive and negative phases, depending on the sign of the NAO anomalies averaged over the May–June period (e.g., Elsner 2003; Kossin et al. 2010; Villarini et al. 2012). Regarding ENSO, the selection is based on the classification of positive/neutral/negative phase according to the NWS Climate Prediction Center (www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml) for August–October. Table ES1 provides a summary of the years classified according to values of the associated state of ENSO and the NAO.

RESULTS. Over the period 1981–2011, over 100 TCs affected the United States, with the eastern seaboard and Florida being the areas that were the most affected (Fig. ES1). For each of these storms, we have created flood ratio maps by interpolating the values among the different stream gage stations using the inverse distance weighting method. Figure 2 shows the spatial extent of flooding associated with two hurricanes making landfall along the U.S. East Coast [Hurricanes Floyd (1999) and Irene (2011)] and two hurricanes making landfall in the Gulf of Mexico [Katrina (2005) and Ike (2008)]. There are large areas in the path of these storms with flood ratios larger than 2:

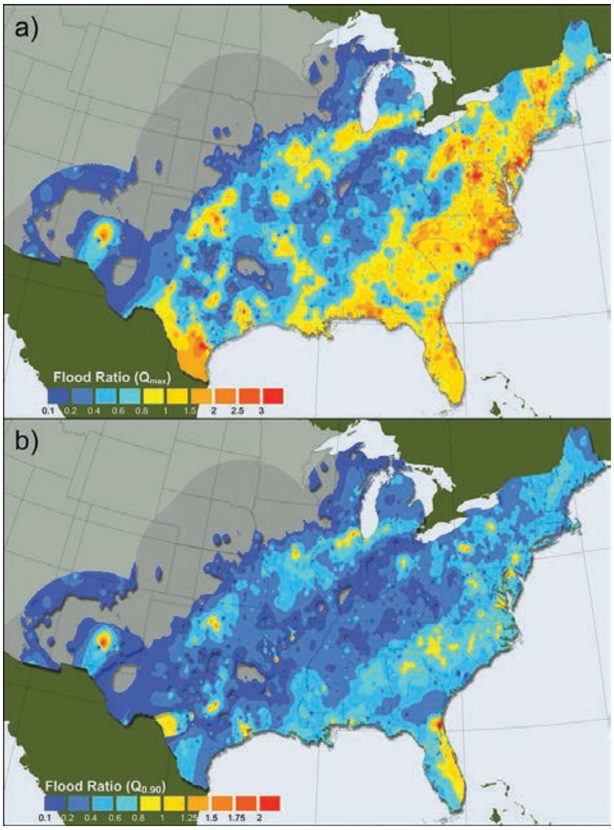

Fig. 3. Spatial interpolation of the (a) maximum and (b) 90th percentile of the flood ratio values associated with TCs at each location. The darker shades of gray represent the extent of the 500-km buffer around the center of circulation for all the storms during the study period. Note that the color bar in the two panels spans over different ranges.

these hurricanes caused flood peaks that were more than twice as large as the corresponding 10-yr flood peak, and that would be generally classified as major flooding according to the NWS classification (Fig. 1). Some of the largest flood ratios over the past 30 years are associated with Hurricane Irene, with flood ratio values larger than 3. Maps of this kind provide key information necessary to highlight the prevalence of TC-related flooding away from the coast. Moreover, as is shown by creating the flood ratio maps for the recent Hurricanes Isaac (2012) and Sandy (2012) (Fig. ES2), it is also possible to create the flood ratio maps shortly after the TC landfall, providing valuable information for a more targeted recovery effort by the emergency services, and a first-order assessment of the inland areas that may suffer from major damage.

By examining all the flood peaks associated with landfalling TCs over the past 31 years, we are able to provide a climatological view of the areas of the United States that have been most affected by these catastrophic events, as summarized in Fig. 3. There are large areas of the study region with flood peak values exceeding the 10-yr flood peaks. Most of the largest flood ratio values are located along the eastern seaboard, from North Carolina to Vermont. The Appalachian Mountains represent a natural divide, shielding the western part of the domain. Other areas with flood ratios larger than 1 are the coastal regions, in particular from coastal Louisiana to Florida. We also observe a local minimum in Georgia, consistent with results related to the climatology of heavy rainfall associated with landfalling TCs (e.g., Hart and Evans 2001; Kunkel et al. 2010; Villarini and Smith 2010; Barlow 2011). These conclusions hold regardless of whether we examine the largest TC flood ratio (Fig. 3a) or the 90th percentiles of the flood ratios (Fig. 3b), indicating that these features are not related to a single event but are more persistent.

It is clear in Fig. 3 that TCs are an important flood agent not only for the eastern United States, but also for large areas of the central United States. This secondary swath is generally associated with storms making landfall along the Gulf of Mexico and then moving northward over the U.S. Midwest. While the magnitude of these flood peaks is not as large as over the eastern United States, TCs can still cause major flooding. Notably, areas that have been impacted include major U.S. Midwest cities, such as St. Louis, Kansas City, Chicago, and Detroit. These results differ from what one may have inferred from previous analyses that were focused on heavy rainfall associated with TCs (e.g., Kunkel et al. 2010; Barlow 2011), as these regions did not stand out as substantially affected by heavy rainfall from TCs. These differences highlight the role of land use/land cover properties and antecedent soil moisture conditions to flooding.

After having characterized the role of North Atlantic TCs as flood agents over the United States, we examine whether there is a relationship between the number and magnitude of TC floods and large-scale climate indices, more specifically NAO and ENSO. Let us start with the NAO (Fig. 4). Most of the TC flood peaks tend to occur during the negative phase of the NAO, in particular over the areas west of the Appalachian Mountains (Figs. 4e,f). These results are consistent with the role played by the NAO in steering these storms (e.g., Elsner 2003; Elsner et al. 2000; Kossin et al. 2010; Colbert and Soden 2012). During the negative phase of the NAO, the Bermuda high tends to shift more toward the eastern Atlantic Ocean, with a larger number of TCs making landfall along the U.S. coast (e.g., Elsner 2003; Villarini et al. 2012). Kossin et al. (2010) found a reduction in the expected number of TCs for increasing NAO values. The phase of the NAO is related not only to the frequency of TC floods, but also to their magnitudes. As shown in Figs. 4a–d, the largest TC flood peaks tend to occur during the negative phase of the NAO, with flood ratio values in excess of 1 over most of the study region. These results suggest that the largest threat posed by North Atlantic TCs in terms of flooding is generally during the negative phase of the NAO.

Figure 5 summarizes the analyses for ENSO. Most of the TC flood peaks over the central part of the study region tend to occur during the neutral phase of the ENSO (Fig. 5h), with a regionally widespread influence during the negative phase (Fig. 5i), in particular in the western part of the domain. This is generally consistent with Elsner (2003), who found that during La Niña years there is a larger probability of straight moving storms making landfall along the Gulf Coast. On the contrary, the link between TCs and floods during El Niño tends to be more restricted to the U.S. East Coast. These results are similar to Kossin et al. (2010), who found that the annual rate of occurrence for TCs in their cluster 1 (they tend to form off of the U.S. East Coast and into the central North Atlantic, with a marked northward component in their tracks) increases for increasing values of the Southern Oscillation index (SOI), with a decrease for the other three clusters with increasing SOI values.

Large TC flood peaks along the U.S. East Coast can occur during any ENSO phase, even though they are more limited to the northeastern United States during La Niña years (Fig. 5c). Over the central United States, the largest flood peaks tend to occur during the neutral and negative ENSO phases (Figs. 5b,c,h,i), with limited activity during El Niño years (Figs. 5a,g). These results indicate that ENSO is not only an important predictor of North Atlantic TC activity, but it also plays a role in the tracking of these storms.

CONCLUSIONS AND DISCUSSION. This study focused on flooding over the continental United States associated with North Atlantic TCs during the period 1981–2011. Analyses were based on USGS discharge measurements and provided a characterization of the U.S. regions that are more affected by this natural hazard. Our findings indicate that TCs are responsible for large flooding over the eastern United States, from Florida to Vermont and Maine. Moreover, there is a secondary swath of enhanced TC flooding over the central United States, as far north and west as Illinois, Wisconsin, and Michigan. Overall, the results of this study highlight a broad impact of TCs through

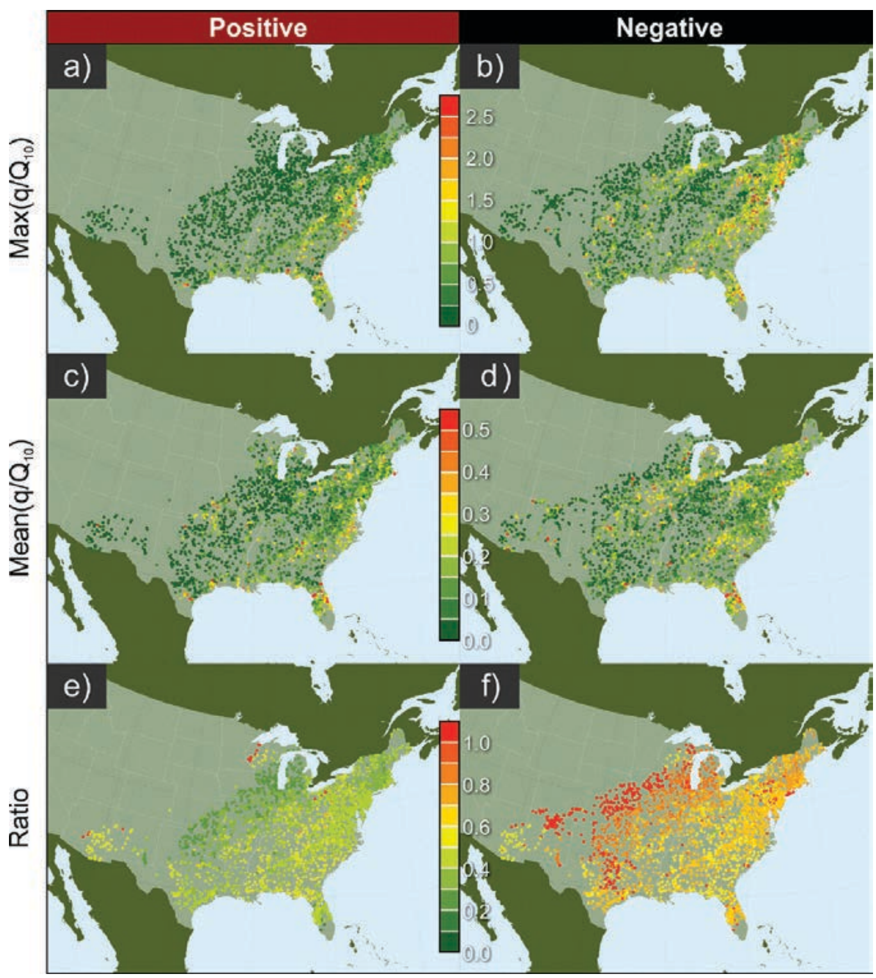

Fig. 4. Examination of the dependence of TC flood number and magnitude on the (left) positive and (right) negative phase of the NAO (consult Table ES1 in the supplemental material for a list of years in each phase). Shown are the (a),(b) largest and (c),(d) mean flood ratio values during each NAO phase, and (e),(f) the proportion of TC flood peaks with respect to the total number of TC flooding occurring during the two NAO phases.

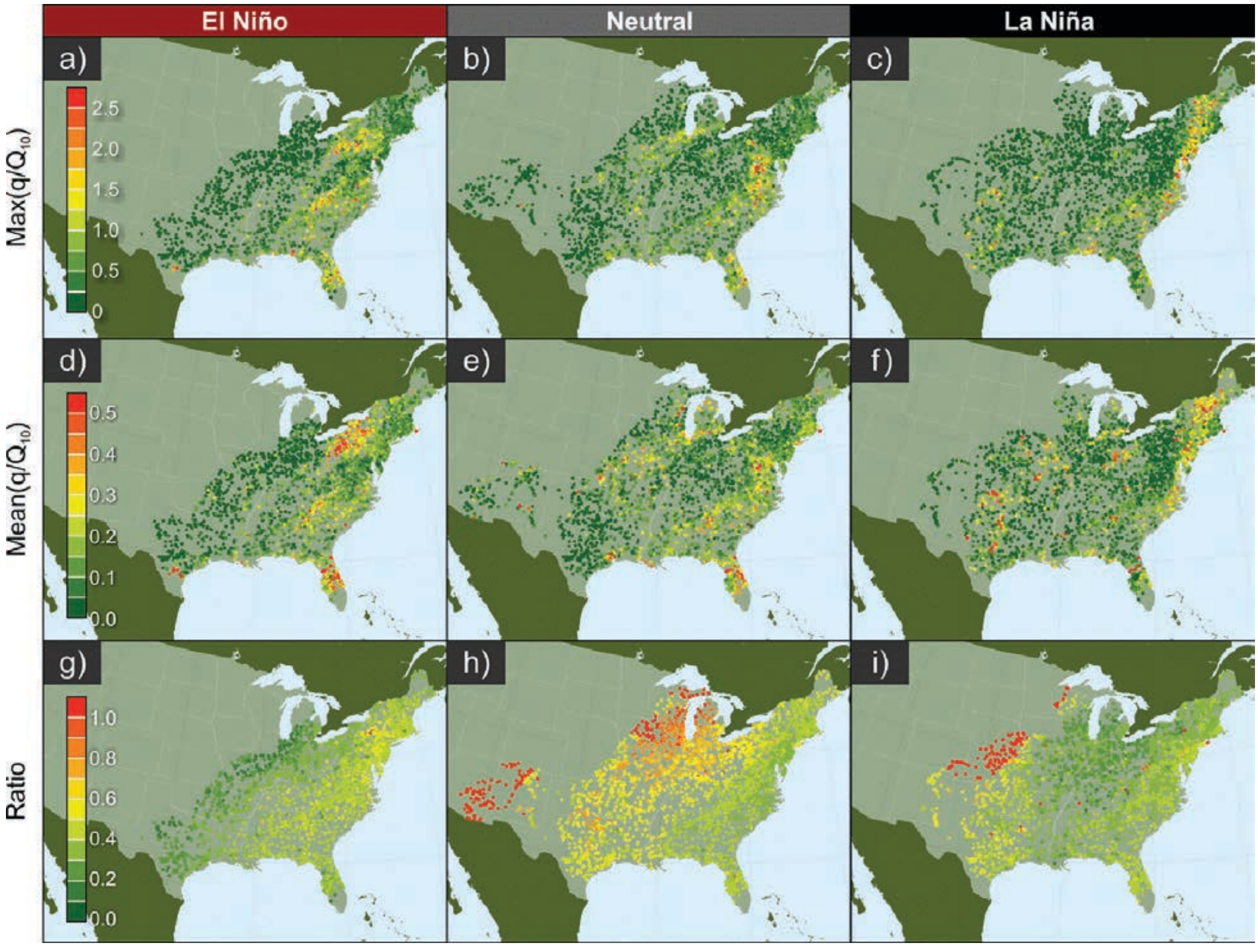

Fig. 5. Examination of the dependence of TC flood number and magnitude on the (left) El Niño, (middle) neutral, and (right) La Niña phase of the ENSO (consult Table ES1 for a list of years in each phase). Shown are the (a)–(c) largest and (d)–(f) mean flood ratio values during each ENSO phase, and (g)–(i) the proportion of TC flood peaks with respect to the total number of TC flooding occurring during the three ENSO phases.

inland flooding. This is in contrast with storm surge and wind damage arising from TCs, which are rather localized phenomena affecting limited areas that are concentrated near the landfall location.

Examination of the relationship between TC flooding and large-scale climate indices uncovered the role played by NAO and ENSO. Most of the TC flood peaks tend to occur during the negative phase of the NAO, which is also associated with some of the largest flood peak magnitudes. Depending on the phase of ENSO, different areas of the study region are more affected. During El Niño years, the U.S. East Coast is affected more than during neutral or La Niña years, in which the center of action shifts toward the central United States. While previous studies have examined the role of ENSO in the genesis and development of North Atlantic TCs, these results support the notion that ENSO plays also a role in the tracking of these storms, as recently discussed in Kossin et al. (2010). Although we have not explored the relationship of the different "flavors" of ENSO (e.g., "Dateline" versus conventional El Niño events) on flood statistics, subsequent analysis should focus on the potential for distinct impacts given the different teleconnections associated with each type of ENSO (e.g., Larkin and Harrison 2005; Kim et al. 2009) These relationships between TC flooding and NAO and ENSO can provide basic information related to the areas of the United States that are more at risk from flooding associated with North Atlantic TCs depending on the values of these indices. Future work should explore the mechanisms behind, and the potential for extended range prediction arising from, these relationships between inland TC-flooding and large-scale atmospheric and oceanic conditions.

The results of this study represent a key step toward a better understanding and characterization of flooding associated with North Atlantic TCs, yet they also highlight gaps in our understanding. As even the basic climatology of inland TC flooding had been previously uncharacterized, the character of past and possible future variations of this hazard remains unexplored, as do possible connections between it and climate variation and change. Understanding these potential climate connections takes on particular importance given both the broad footprint of TC-related inland freshwater flooding and the strong consensus among modeling studies for an increase in TC rainfall over the coming century (e.g., Knutson et al. 2010, 2013). Because the inland impacts are much larger than previously thought based on rainfall analyses, they indicate that for large areas of the United States awareness about this flood hazard should potentially be increased.

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REFERENCES

Barlow, M., 2011: Influence of hurricane-related activity on North American extreme precipitation. *Geophys. Res. Lett.,* **38,** L04705, doi:10.1029/2010GL046258.

Bove, M. C., J. B. Elsner, C. W. Landsea, X. Niu, and J. J. O'Brien, 1998: Effect of El Niño on U.S. landfalling hurricanes, revisited. *Bull. Amer. Meteor. Soc.,* **79,** 2477–2482, doi:10.1175/1520-0477(1998)0792.0.CO;2.

Camargo, S. J., K. A. Emanuel, and A. H. Sobel, 2007: Use of a genesis potential index to diagnose ENSO effects on tropical cyclone genesis. *J. Climate,* **20,** 4819–4834, doi:10.1175/JCLI4282.1.

Changnon, S. A., 2008: Assessment of flood losses in the U.S. *J. Contemp. Water Res. Educ.,* **138,** 38–44, doi:10.1111/j.1936-704X.2008.00007.x.

Colbert, A. J., and B. J. Soden, 2012: Climatological variations in North Atlantic tropical cyclone tracks. *J. Climate,* **25,** 657–673, doi:10.1175/JCLI-D-11-00034.1.

Czajkowski, J., G. Villarini, E. Michel-Kerjan, and J. A. Smith, 2013: Determining tropical cyclone inland flooding loss on a large scale through a new flood peak ratio-based methodology. *Environ. Res. Lett.,* **8,** 044056, doi:10.1088/1748-9326/8/4/044056.

Elsberry, R., 2002: Predicting hurricane landfall precipitation: Optimistic and pessimistic views from the Symposium on Precipitation Extremes. *Bull. Amer. Meteor. Soc.,* **83,** 1333–1339.

Elsner, J. B., 2003: Tracking hurricanes. *Bull. Amer. Meteor. Soc.,* **84,** 353–356, doi:10.1175/BAMS-84-3-353.

——, K. B. Liu, and B. Kocker, 2000: Spatial variations in major U.S. hurricane activity: Statistics and a physical mechanism. *J. Climate,* **13,** 2293–2305, doi:10.1175/1520-0442(2000)0132.0.CO;2.

——, X. Niu, and T. H. Jagger, 2004: Detecting shifts in hurricane rates using a Markov chain Monte Carlo approach. *J. Climate,* **17,** 2652–2666, doi:10.1175/1520-0442(2004)017<2652:DSIHRU>2.0.CO;2.

Groisman, P. Ya., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore, 2004: Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *J. Hydrometeor.,* **5,** 64–85, doi:10.1175/1525-7541(2004)0052.0.CO;2.

Gupta, V. K., O. J. Mesa, and D. R. Dawdy, 1994: Multiscaling theory of flood peaks: Regional quantile analysis. *Water Resour. Res.,* **30** (12), 3405–3421, doi:10.1029/94WR01791.

Hart, R. E., and J. L. Evans, 2001: A climatology of the extratropical transition of Atlantic tropical cyclones. *J. Climate,* **14,** 546–564, doi:10.1175/1520-0442(2001)0142.0.CO;2.

Hellin, J., M. Haigh, and F. Marks, 1999: Rainfall characteristics of Hurricane Mitch. *Nature,* **399,** 316, doi:10.1038/20577.

Jonkman, S. N., B. Maaskant, E. Boyd, and M. L. Levitan, 2009: Loss of life caused by the flooding of New Orleans after Hurricane Katrina: Analysis of the relationship between flood characteristics and mortality. *Risk Anal.,* **29** (5), 676–698, doi:10.1111/j.1539-6924.2008.01190.x.

Kim, H.-M., P. J. Webster, and J. A. Curry, 2009: Impact of shifting patterns of Pacific Ocean warming on North Atlantic tropical cyclones. *Science,* **325,** 77–80, doi:10.1126/science.1174062.

Knight, D. B., and R. E. Davis, 2009: Contribution of tropical cyclones to extreme rainfall events in the southeastern United States. *J. Geophys. Res.,* **114,** D23102, doi:10.1029/2009JD012511.

Knutson, T. R., and Coauthors, 2010: Tropical cyclones and climate change. *Nat. Geosci.,* **3,** 157–163, doi:10.1038/ngeo779.

——, and Coauthors, 2013: Dynamical downscaling projections of twenty-first-century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *J. Climate,* **26,** 6591–6617, doi:10.1175/JCLI-D-12-00539.1.

Konrad, C. E., and L. B. Perry, 2010: Relationships between tropical cyclones and heavy rainfall in the Carolina region of the USA. *Int. J. Climatol.,* **30,** 522–534.

Kossin, J. P., S. J. Camargo, and M. Sitkowski, 2010: Climate modulation of North Atlantic hurricane tracks. *J. Climate,* **23,** 3057–3076, doi:10.1175/2010JCLI3497.1.

Kunkel, K. E., D. R. Easterling, D. A. R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2010: Recent increases in U.S. heavy precipitation associated with tropical cyclones. *Geophys. Res. Lett.,* **37,** L24706, doi:10.1029/2010GL045164.

Larkin, N. K., and D. E. Harrison, 2005: On the definition of El Niño and associated seasonal average U.S. weather anomalies. *Geophys. Res. Lett.,* **32,** L13705, doi:10.1029/2005GL022738.

Larson, J., Y. Zhou, and R. W. Higgins, 2005: Characteristics of landfalling tropical cyclones in the United States and Mexico: Climatology and interannual variability. *J. Climate,* **18,** 1247–1262, doi:10.1175/JCLI3317.1.

Latif, M., N. Keenlyside, and J. Bader, 2007: Tropical sea surface temperature, vertical wind shear, and hurricane development. *Geophys. Res. Lett.,* **34,** L01710, doi:10.1029/2006GL027969.

Mendelsohn, R., K. Emanuel, S. Chonabayashi, and L. Bakkensen, 2012: The impact of climate change on global tropical cyclone damage. *Nat. Climate Change,* **2,** 205–209, doi:10.1038/nclimate1357.

National Weather Service, 2012: Definitions and general terminology. National Weather Service Manual 10-950, Operations and Services, Hydrologic Services Program, NWSPD 10-9, 5 pp. [Available online at www.nws.noaa.gov/directives/sym/pd01009050curr.pdf.]

Peduzzi, P., B. Chatenoux, H. Dao, A. De Bono, C. Herold, J. Kossin, F. Mouton, and O. Nordbeck, 2012: Global trends in tropical cyclone risk. *Nat. Climate Change,* **2,** 289–294, doi:10.1038/nclimate1410.

Pielke, R. A., 2009: United States hurricane landfalls and damages: Can one- to five-year predictions beat climatology? *Environ. Hazards,* **8,** 187–200, doi:10.3763/ehaz.2009.0017.

——, J. Gratz, C. W. Landsea, D. Collins, M. A. Saunders, and R. Musulin, 2008: Normalized hurricane damage in the United States: 1900–2005. *Nat. Hazards Rev.,* **9** (1), 29–42, doi:10.1061/(ASCE)1527-6988(2008)9:1(29).

Rappaport, E. N., 2000: Loss of life in the United States associated with recent Atlantic tropical cyclones. *Bull. Amer. Meteor. Soc.,* **81,** 2065–2073, doi:10.1175/1520-0477(2000)0812.3.CO;2.

Rowe, S. T., and G. Villarini, 2013: Flooding associated with predecessor rain events over the Midwest United States. *Environ. Res. Lett.,* **8,** 024007, doi:10.1088/1748-9326/8/2/024007.

Shepherd, J. M., A. Grundstein, and T. L. Mote, 2007: Quantifying the contribution of tropical cyclones to extreme rainfall along the coastal southeastern United States. *Geophys. Res. Lett.,* **34,** L23810, doi:10.1029/2007GL031694.

Smith, J. A., G. Villarini, and M. L. Baeck, 2011: Mixture distributions and the climatology of extreme rainfall and flooding in the eastern United States. *J. Hydrometeor.,* **12,** 294–309, doi:10.1175/2010JHM1242.1.

Sturdevant-Rees, P. L., J. A. Smith, J. Morrison, and M. L. Baeck, 2001: Tropical storms and the flood hydrology of the central Appalachians. *Water Resour. Res.,* **37** (8), 2143–2168, doi:10.1029/2000WR900310.

Tippett, M. K., S. J. Camargo, and A. H. Sobel, 2011: A Poisson regression index for tropical cyclone genesis and the role of large-scale vorticity in genesis. *J. Climate,* **24,** 2335–2357, doi:10.1175/2010JCLI3811.1.

U.S. Department of Commerce, Service Assessment Hurricane Irene, August 21–30, 2011. 129 pp. [Available online at www.nws.noaa.gov/om/assessments/pdfs/Irene2012.pdf.]

Vecchi, G. A., and B. J. Soden, 2007: Effect of remote sea surface temperature change on tropical cyclone potential intensity. *Nature,* **450,** 1066–1070, doi:10.1038/nature06423.

Villarini, G., and J. A. Smith, 2010: Flood peak distributions for the eastern United States. *Water Resour. Res.,* **46**, W06504, doi:10.1029/2009WR008395.

——, and ——, 2013: Flooding in Texas: Examination of temporal changes and impacts of tropical cyclones. *J. Amer. Water Resour. Assoc.,* **49** (4), 825–837, doi:10.1111/jawr.12042.

——, G. A. Vecchi, and J. A. Smith, 2010: Modeling of the dependence of tropical storm counts in the North Atlantic basin on climate indices. *Mon. Wea. Rev.,* **138,** 2681–2705, doi:10.1175/2010MWR3315.1.

——, J. A. Smith, M. L. Baeck, T. Marchok, and G. A. Vecchi, 2011: Characterization of rainfall distribution and flooding associated with U.S. landfalling tropical cyclones: Analyses of Hurricanes Frances, Ivan, and Jeanne (2004). *J. Geophys. Res.,* **116,** D23116, doi:10.1029/2011JD016175.

——, G. A. Vecchi, and J. A. Smith, 2012: U.S. landfalling and North Atlantic hurricanes: Statistical modeling of their frequencies and ratios. *Mon. Wea. Rev.,* **140,** 44–65, doi:10.1175/MWR-D-11-00063.1.

Vimont, D. J., and J. P. Kossin, 2007: The Atlantic meridional mode and hurricane activity. *Geophys. Res. Lett.,* **34,** L07709, doi:10.1029/2007GL029683.

Zandbergen, P., 2009: Exposure of US counties to Atlantic tropical storms and hurricanes, 1851–2003. *Nat. Hazards,* **48,** 83–99, doi:10.1007/s11069-008-9250-6.

THE DYNAMICS OF HURRICANE RISK PERCEPTION

Real-Time Evidence from the 2012 Atlantic Hurricane Season

BY ROBERT J. MEYER, JAY BAKER, KENNETH BROAD, JEFF CZAJKOWSKI, AND BEN ORLOVE

Surveys of coastal residents conducted in 2012 as hurricanes were approaching reveal widespread misunderstanding of the extent and nature of threats posed by tropical cyclones.

Over the past century, hurricanes have been the single largest source of property damage from natural hazards in the United States. In the last decade alone, losses from hurricanes have been estimated at $290 billion (2012 U.S. dollars), with two storms—Katrina in 2005 and Sandy in 2012—collectively inflicting over $120 billion in damage (Blake et al. 2011, 2013; Pielke et al. 2008; Pielke 2012). What makes the scale of these losses particularly troublesome is that hurricanes are now among the best understood of all natural hazards, and in recent years there have been dramatic increases in track forecasting abilities and warning times (e.g., Cangialosi and Franklin 2013; Gall et al. 2013). These scientific advances, however, have seemingly not been matched by commensurate increases in preventive adaptation. To illustrate, 36 hours in advance of Hurricane Sandy residents were warned that the storm would likely bring "life-threatening storm surge flooding" to the Northeast (NWS 2012). Yet, 230,000 cars were still lost in the storm from floods (Taylor 2013)—a loss that, at least in hindsight, would seem to have been avoidable.

This article reports the findings of a unique program of research designed to shed light on potential reasons for this adaptation paradox. We report data from field surveys that measured the evolution of coastal residents' risk perceptions and preparation plans as two hurricanes—Isaac and Sandy—approached the United States during the 2012 hurricane season. In these studies, perceptions and preparation decisions were measured in real time as they were being made by residents threatened by the storms. These data thus provide the first longitudinal look at how hurricane risk perceptions and responses evolve over time during storm threats and how these perceptions compared to the objective risks residents were facing.

The data yield a surprising—and potentially disturbing—view of hurricane threat response. Despite

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the ubiquity of information available about Isaac and Sandy, residents misperceived the actual risks that they faced in terms of the intensity, nature, and duration of impacts. Surveyed residents, for example, overestimated the probability that their homes would be affected by hurricane-force winds, but then they displayed limited degrees of concern over this prospect. These residents also underestimated the threat posed by flooding—including people living adjacent to water areas. The consequence was a systematic pattern of miscalibrated preparation decisions, with residents taking actions that were suitable for a short-lasting wind event but not for a significant wind or flood catastrophe with a long-term recovery period for which evacuation would be required. In addition, these misperceptions also appeared to be manifested in longer-term investments in protection; only 54% of residents living within a half mile of water areas threatened by Sandy, for example, reported holding separate flood insurance policies. These issues point to the importance of adjusting hurricane warnings and information campaigns, and of evaluating policy options in the light of these misunderstandings of hurricane hazards.

BACKGROUND AND METHOD. Over the years, a large survey-based literature has been developed that describes the kinds of beliefs coastal residents have about the long-term risk posed by hurricanes (e.g., Peacock et al. 2005; Trumbo et al. 2011), as well as the basis of shorter-term preparation decisions, particularly those involving evacuation (e.g., Baker 1991; Dash and Gladwin 2007; Dow and Cutter 1998; Huang et al. 2012; Lindell et al. 2005; Lindell and Prater 2008; Morss and Hayden 2010; Zhang et al. 2007). While this work has been useful in providing insights into such issues as the intrahousehold drivers of decisions to evacuate (e.g., Baker 1991; Lindell and Prater 2008) and media utilization during storms (e.g., Zhang et al. 2007; Broad et al. 2007), it has been less informative about how residents perceive hurricane threats when they are arising and about the accuracy of decisions to take protective action. One primary reason for this gap is that past findings have been based on surveys conducted weeks or even years after storms have past, when memories of what risk perceptions were *before* the storm and the process by which preparation decisions were made may have faded and were possibly distorted by hindsight bias (e.g., Brown et al. 1994; Fischhoff and Beyth 1975).[1] As a result, we know little about how risk perceptions evolve over time as storms move toward a coast when the outcome of a storm is still in doubt and, most critically, about the suitability of preparation actions.

In an attempt to obtain this knowledge, we conducted a program of survey research during the 2012 hurricane season that measured risk perceptions and preparation decisions as they were being made by threatened residents. The storm season offered two opportunities for study: Hurricane Isaac, which made landfall on the coast of the Louisiana just west of the Mississippi River in late August (Berg 2012), and Hurricane Sandy, which made landfall on the coast of New Jersey near Atlantic City in late October (Blake et al. 2012). The surveys were conducted by phone and were initiated 72 hours (for Sandy) or 48 hours (for Isaac) before each storm's predicted landfall and then repeated with different random samples three shifts a day until 6 h before predicted landfall (see Fig. 1). The surveys were timed to allow measures of subjective storm beliefs to be paired with objective storm information carried in the 0500, 1100, and 1700 EDT National Hurricane Center advisories.

Each survey instrument contained between 60 and 80 questions (depending on screens) that focused on five domains: 1) current beliefs about the objective characteristics of the storm and warnings, 2) perceptions of the threat posed by the storm, 3) sources of information about the storm, 4) preparation actions, and 5) personal background characteristics. The nature and wording of the specific items evolved from the experience gained designing two prior real-time survey instruments that were developed for use in 2010 (Hurricane Earl) and 2011 (Hurricane Irene). The 2012 surveys contained several new items not contained in previous versions (e.g., probability assessments for different kinds of threats) and were tested for comprehension by the field survey firm (Kerr and Downs Research) prior to administration.

For the Isaac study, respondents were drawn from a random sample of households in coastal ZIP codes with land telephone lines along the middle Gulf Coast from southeastern Louisiana to Alabama, as well as the two westernmost counties in the Florida

[1] Studies that have directly measured recall accuracy for natural hazards have shown reasonably high test–retest reliability in stated reports, something that would seem to assuage this concern (e.g., Neisser et al. 1996; Norris and Kaniasty 1992). The limitation of this work, however, is that, because there were no measures taken before events, little is known about whether postevent reports are influenced by hindsight bias and the degree to which test–retest reliability was inflated by temporal nonindependence of the measures.

Panhandle (see Fig. 1). For the Sandy study, respondents were drawn from coastal ZIP codes along the mid-Atlantic region from Virginia to northeastern New Jersey. Within each survey shift, approximately 50–60 surveys could be completed, producing a total of 893 completed surveys across both storms. In Table 1 we provide the basic demographic profile of each sample for each storm along with, for comparison, the corresponding 2010 population demographics of the associated counties from which the sample was pooled. While there was some storm-to-storm variation in samples, most participants were homeowners between the ages of 30 and 80 with at least some college education, and approximately three-quarters of participants reported total household incomes over $40,000. As such, the sample tended to be somewhat older, more educated, and more likely to own homes than the mean of the general population in the surveyed areas.

The absolute response rate for the Isaac and Sandy surveys (percentage of phones dialed that yielded a completed survey) was 7.1% for Isaac and 10% for Sandy, a number consistent with recently published norms for telephone surveys in public opinion polls (Pew Research Center 2012, table on p. 5). The realized cooperation rates (the percentage contacted who participated), however, was much higher than the Pew norms, being 39% for Isaac and 49.3% for Sandy. As a point of reference, these cooperation rates are on a par with response rates reported in recent mail-based posthurricane surveys (e.g., Huang et al. 2012).

The location of respondents' vis-à-vis evacuation zones was reasonably well known for Isaac but less so for Sandy, where evacuation orders varied by municipality. As we detail in appendix B [the appendixes are in an online supplement (http://dx.doi.org/10.1175BAMS-D-12-00218.2)], most respondents to the Isaac surveys lived in mandatory evacuation areas (zone A or category 1) with the exception of some in Harrison County, Mississippi, who lived inland from evacuation zones. In most areas in Isaac's track, evacuation was advised both for those in beachfront areas as well as those in low-lying areas and adjacent to streams prone to flooding from rain. Because respondents likely varied in their awareness of such orders, our subsequent analysis will focus on stated awareness rather than actual orders (for which we have incomplete measures).

A natural source of concern when contacting respondents via landlines was the possibility of nonresponse bias due to an increasing tendency for those who were most at risk from the storm (or were most concerned about risk) to leave the study area as the storms approached. Our data offered two means for testing this possibility: by measuring temporal changes in home-contact and survey completion rates over time and by seeing if there were temporal changes in sample demographics that might be associated with decisions to evacuate in past studies (e.g., Lindell et al. 2005; Huang et al. 2012). Because homes were contacted on a randomized basis, nonresponse bias due to evacuation would be evidenced by a decrease in the rate of successful telephone contacts over time as the storm approached. As shown in Fig. 2, however, such a decrease was not observed; indeed, in the case of Sandy, successful contact rates actually *increased* over time—possibly because of more residents being at home due to work cancellations. In the case of Sandy, a logistic trend analysis of the number of homes successfully contacted supported a significant positive trend as the time to landfall wore on (χ^2 (1, N = 9)= 13.77; p =<0.01), whereas there was no significant trend in the case of Isaac (χ^2 (1, N = 6) = 2.28; p = 0.13).

Further reassurance that nonresponse bias was likely not a major factor in our surveys was that the

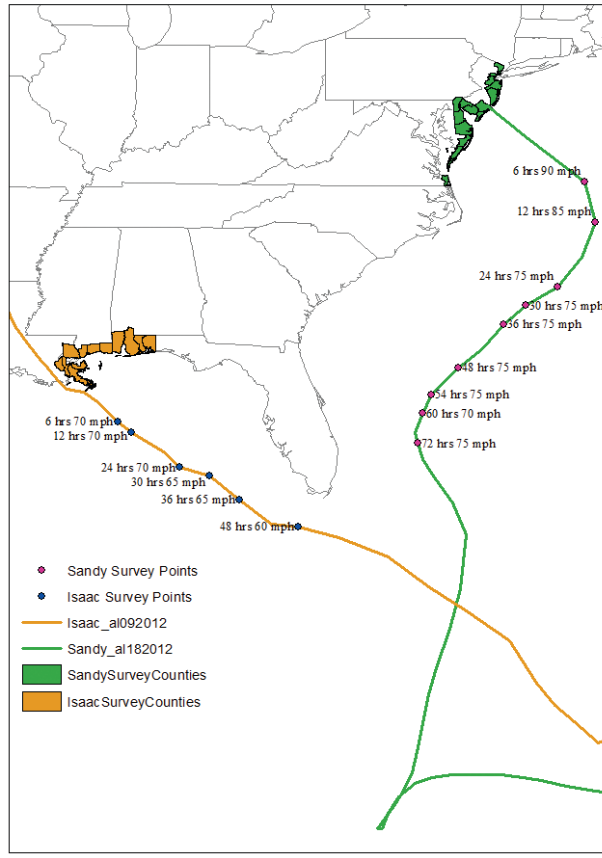

Fig. 1. Storm paths and coastal counties surveyed. Storm paths indicate timing of survey in hours prior to landfall and wind intensity at the storm's center.

demographic profile of the respondent pool remained largely stable over time. For both storms we regressed five different profile variables that have been found in the past to be correlated with propensities to evacuate—age [question (Q) 72; appendix A], education (Q75), past storm damage experience (Q63), gender (Q86), and distance from water (Q80; available only in the Sandy study; e.g., Baker 1991; Lindell and Prater 2008)—with time until landfall. For the Sandy study, none of these univariate analyses could reject a null hypothesis of temporal stationarity. In the Isaac study, there was a significant tendency for the sample to be slightly younger later in the survey period ($t = -2.44$; $p = .015$). Age, however, was separately found not to be a significant predictor of two risk-perception variables that might be associated

Table 1. Respondent socioeconomic/demographic profile summary

Characteristic	Isaac survey respondents (%)	Isaac survey counties (%)	Sandy survey respondents (%)	Sandy survey counties (%)
Homeowner status*				
Homeowner	93	59	89	57
Rent	6	27	9	30
Other/refused/vacant (counties)	1	14	1	13
Age*				
Under 30	3	40	4	39
30–60 (respondents)/30–59 (counties)	52	41	41	42
61–80 (respondents)/60–79 (counties)	34	16	40	15
Over 80 (respondents)/80+ (counties)	6	3	8	4
Other/refused	5	—	7	—
Race*				
African American or black	13	22	8	13
Caucasian or white	83	71	83	69
Other/refused	4	7	9	18
Education level**				
Some high school/high school graduate	25	42	26	41
Some college/college graduate	53	46	48	43
Postgraduate	14	7	20	10
Other/refused/less than high school (counties)	8	5	6	6
2011 total household income**				
Less than $15,000	5	13	2	11
$15,000–$39,999 (respondents)/ $15,000–$34,999 (counties)	16	23	10	19
$40,000–$79,999 (respondents)/ $35,000 to $74,999 (counties)	25	33	14	31
Over $80,000 (respondents)/ over $75,000 (counties)	21	31	23	39
Other/refused	33	—	51	—
Resident type				
Live here year-round	98	—	97	—
Vacationing	2	—	1	—
Other/refused	0	—	2	—

* County data from 2010 U.S. census.

** County data from 2007–2011 American Community Survey. Education level based on total population of residents that are 25 years old and older (approximately 88% of the total adult population). 2011 total household income based on occupied (owner and renter) housing units income data in 2011 inflation-adjusted dollars.

with decisions to evacuate in the absence of an order: ratings of perceived safety in home and probability of wind damage.[2]

FINDINGS. The survey data provided a rich array of cross-sectional and spatial–temporal data about storm knowledge, perceptions, and preparation actions. Below we report the most salient features of these data, focusing on three categories: awareness of the storms and warnings, the accuracy of the mental models that residents held about storm threats, and the suitability of short- and long-term preparations. In appendix C the sample sizes underlying each figure are reported.

Storm and warning awareness. Both Isaac and Sandy were major local, regional, and national media events. Local news stations provided continuous coverage of the storm from the time warnings were first issued until after landfall, and the Weather Channel set an all-time viewership record during Sandy, when 39 million U.S. households tuned in to watch the television network's coverage on 29 October (Bibel 2012). This impact was matched by high levels of web viewing, with the Weather Channel web-based platforms (weather.com, mobile apps) receiving over 450 million page views that same day (Bibel 2012).

Reflecting this ubiquity of media attention, survey respondents displayed universal (100%) awareness of each storm (Q1), with respondents indicating that they were keeping regularly abreast of storm information. Across all time periods, 88% of Isaac respondents indicated having received their latest information (from any source) within the previous 2 hours (Q23), as did 79% in Sandy. The primary source of this information (Q24) was television for 90% of respondents in Isaac and 87% in Sandy. In contrast, Internet websites and social media were less commonly utilized; 21% of respondents in Isaac and 15% in Sandy reported that their last information came from any Internet source (either alone or in conjunction with TV) and, of the 43% of respondents across both storms who had a social media account (e.g., Facebook, Twitter), only 4.5% indicated that it was used as a source of storm information.[3]

Despite the high awareness of the storm threats and frequent monitoring of information, respondents' knowledge about the warnings that had been issued

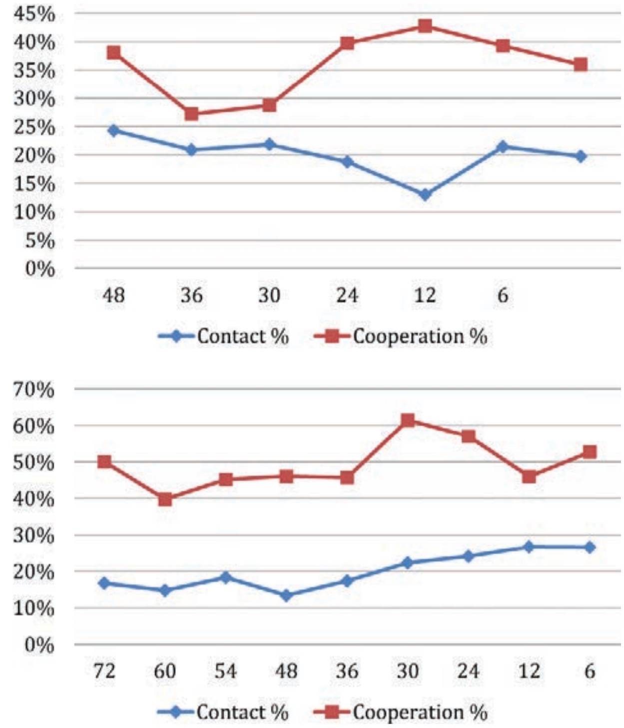

FIG. 2. Successful telephone contact and conditional survey completion rates in hours prior to landfall (*x* axis) for (top) Isaac and (bottom) Sandy.

for their locations was surprisingly imperfect. For example, during our Isaac surveys, hurricane warnings were continuously in effect in Louisiana and Mississippi, with watches in Alabama and Florida. Nevertheless, when asked 11% of respondents were unaware or unsure whether watches or warnings of any kind had been issued (Q13), and among those who were aware only 66% who were under a hurricane warning correctly reported this (Q14).[4] Likewise, in the 36 hours just before Sandy made landfall, 20% of respondents in coastal New Jersey, Delaware, and Maryland (the main threat areas that were sampled) were still unaware or uncertain whether warnings had been issued for their areas, and of those aware 40% thought it was something other than a hurricane warning.

What makes this result somewhat surprising is that residents in both studies had recent experience with tropical cyclones and, as noted, media coverage of both storms was extensive. The surveyed area of the Gulf Coast, for example, had been under some kind of tropical cyclone warning five times since 2008, and

[2] Details of these analyses are available upon request.

[3] It is possible, of course, that respondents were using social media for functions other than as a source of factual storm information.

[4] The most common error was to believe that they were still under a hurricane watch (22% in Isaac and 27% in Sandy).

the mid-Atlantic region had been affected by hurricane Irene just the year before (Avila and Cangialosi 2011). One possible explanation for particularly high rates of confusion in Sandy, however, is that as the storm approached the coast the National Hurricane Center decided to switch from issuing traditional hurricane watches and warnings to "hurricane wind warnings" in anticipation of an extratropical transition prior to landfall (Blake et al. 2012).

Accuracy of mental models: Misperceiving intensity and impact. In addition to misconstruing warnings, residents also displayed relatively poor mental models of the meteorological threats each storm posed. [Mental models are the cognitive representations of real-world objects, events, and processes that people form in their minds (Jones et al. 2011).] The data suggest that

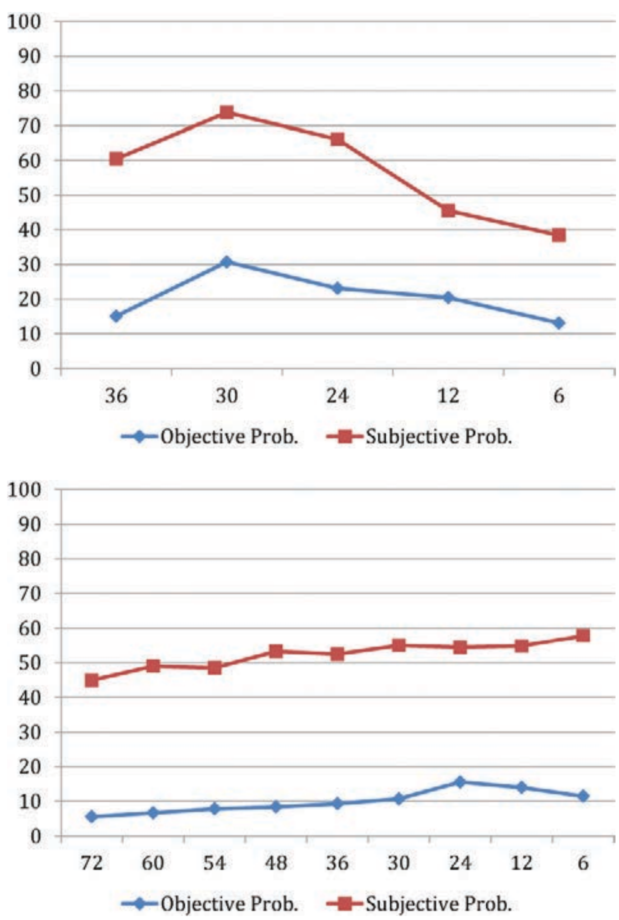

Fig. 3. Respondents' beliefs about the probability that their homes would experience hurricane winds of 75 mph or higher (red line) and corresponding objective probabilities (blue line) in hours until expected landfall (*x* axis) for (top) Isaac and (bottom) Sandy. Isaac data cover only the last 36 hours because of a survey error in which the wind speed question was not asked in the first survey wave.

perceptions were marked by two prominent biases: an *overestimation of wind intensity*—believing hurricane wind conditions winds were far more likely to occur than was actually the case—and an *underestimation of impact*—being relatively unconcerned about the prospect of such winds and a tendency to underestimate the threat posed by storm surge and flooding.

To illustrate these biases, in Fig. 3 we plot the time course of respondents' subjective beliefs about the probability that their homes would experience hurricane-force winds of 75 mph (33.5 m s^{-1}) or greater (Q16; red line) along with the corresponding *objective* probabilities derived from the National Hurricane Center wind forecasts, pooled across states. The objective benchmarks were constructed using the published cumulative hurricane-force wind probability in a given advisory for the city closest to residents' location. For example, in Sandy the benchmark forecasts were Norfolk for southeastern Virginia (VA), Ocean City for Maryland (MD) and Delaware (DE), and either Atlantic City or Newark for New Jersey (NJ).

The data show that residents systematically overestimated their likelihood of experiencing hurricane-force winds, with estimates, at times, averaging 5 times those of the scientific estimates for both storms. For example, as Sandy was approaching coastal New Jersey, the National Hurricane Center cumulative hurricane wind probability at Atlantic City remained below 30%, yet the New Jersey sample consistently reported subjective estimates between 70% and 80%.

But while residents fully expected the arrival of a hurricane, paradoxically few of them expressed high degrees of worry over this prospect. Respondents were asked a number of questions designed to elicit expected personal storm impacts, including rating (on a 100-point scale) how safe they felt riding out the storm in their homes (Q30), the probability that the winds would be such to risk property damage (Q17), the probability that property damage might be such as to threaten personal safety (Q18), and whether they believed that the storm would hit and be a danger to them (Q31). In Fig. 4 we plot the time course of these multiple measures, which shows that residents' high expectations of experiencing hurricane-force winds shown earlier (Fig. 3) were not manifested in high levels of concern about these winds.

For example, across all time periods only 13% of respondents threatened by Isaac and only 17% in the case of Sandy thought that the storm posed personal danger. Likewise, the judged probability that the winds would be strong enough to inflict some kind of property damage was consistently lower than the probability that the winds would be of hurricane force. For example, in the survey period before expected landfall in Isaac, the average judged probability of hurricane force winds was 40% (Fig. 3), but the average judged probability of property damage was 22% for any personal danger (with the likelihood of severe damage being predictably lower). Likewise, in the last survey period before landfall in Sandy, the average judged probability of hurricane force winds was 58%, but the average judged probability of any property damage was 30%.

A potentially more worrisome aspect of the findings, however, is that the data also show evidence that residents consistently misperceived the likely *source* of the danger posed by both storms, with residents for whom the greatest objective threat was from water believing it was from wind. While we lack specific objective information about the actual primary threat faced by each respondent, we can form tentative inferences about the accuracy of risk beliefs by examining how they covaried with factors inherently associated with water and wind risk, such as the respondent's proximity to water (Q80), whether the person lived in an evacuation zone (either objective or perceived; Q44), and building type (Q55).

The survey provided two measures of respondents' beliefs about the relative threat posed by wind versus water: a question that asked which of six impacts posed the greatest threat from each storm (wind, flooding from storm surge, a combination of wind and surge, flooding from rain, tornadoes, or some other impact; Q32), and their subjective probabilities that they would experience damage to home or safety from wind or flood (Q17–22). As noted above, for each hazard we asked respondents to assess the probability of property damage alone as well as the probability that the damage would be severe enough to threaten personal safety (e.g., Q17 vs Q18). To construct a composite index, we first took the average of these probability assessments for flood, and then we subtracted it from the corresponding average for wind. In the Isaac surveys, the flood threat was asked only in terms of storm surge; however, in the Sandy surveys, we solicited separate probabilities for the risk of flood from storm surge and that from rain. In this latter case, we defined the subjective water threat as the larger of these two mean stated probabilities.

As we noted earlier, almost all of the Isaac surveys were conducted among individuals living in either zone A or category 1 surge zones, where evacuations had been ordered in advance of the storm (see appendix B). Despite this location, 56% of respondents identified the greatest threat they faced was that of wind, while only 33% identified either surge flooding or combined wind and surge flooding as the major threat. Likewise, the mean stated probability of damage from wind was 7% higher than that for water across Isaac respondents.

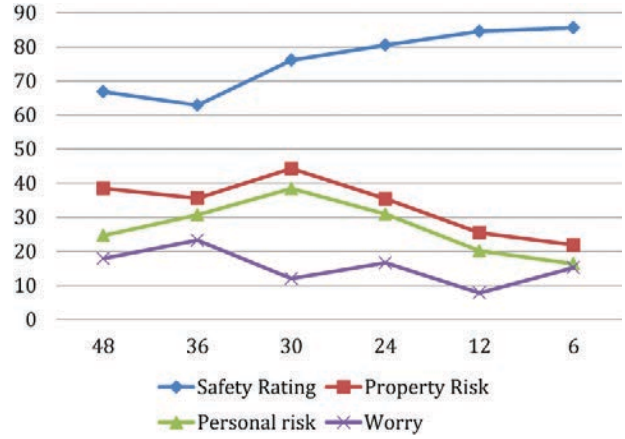

Fig. 4. Evolution of perceptions of personal risk as a function of hours until expected landfall for (top) Isaac and (bottom) Sandy. Safety rating is a rating on a 1–100 scale of how safe respondents felt riding out the storm in their homes with 0 as not safe at all and 100 as certain of safety. Property risk is the judged probability that the storm's winds would induce property damage, personal risk is the probability that the damage would be severe enough to threaten personal safety with 0 as no chance of damage or danger and 100 as certain of damage or danger. "Worry" is the percentage of respondents who indicated that that they believed that the storm would hit and pose a danger to them.

Of course, one explanation for this result is that respondents were unaware that they were living in flood-prone areas (a common finding in past evacuation studies; e.g., Baker 2005a,b; Arlikatti et al. 2006). To test for this, in Fig. 5a we plot the distribution of primary threat beliefs by two indicators of water threat that would have been salient to residents: whether they had heard they were living in an area where evacuations had been ordered (Q44) and whether they were living within 500 feet of the Gulf Coast (or, in the Louisiana sample, Lake Ponchartrain), as computed from geocoded linear distance [$N = 40$ within 500 ft (152 m) and $N = 314$ beyond 500 ft].

The figures show that while living adjacent to the water indeed heightened concerns about flooding, a plurality—40% within 500 ft of the water—still believed that the primary threat was from wind, and beliefs about the larger threat of wind were actually *higher* among those who had heard that they were living in an area where evacuations had been ordered.

Because we gathered a richer array of measures about location and beliefs in the Sandy study, it allowed us to undertake a more detailed analysis of wind-versus-water misperceptions. In Fig. 5b we plot two measures of the relative degree to which residents believed the greatest threat was from wind over water as a function of the distance of a residents' home from a water body (Q80): the wind-bias index described above (the difference between the subjective probability of damage from wind vs water), and the difference between the proportion of respondents who identified wind as the greatest source of threat versus *any* water threat (Q32; surge, wind and surge, rain). While here we see that, indeed, awareness of the threat of water grew as the respondent's proximity to water grew, both the wind-bias indices are always strictly positive; even those living on the water believed that the greater threat they faced was from wind rather than water.

Because the probability-based wind-bias index appeared to be the measure of relative belief that was most responsive to variation in objective risk, as a final analysis on the Sandy data we regressed this bias measure against a battery of indicator-coded variables that capture the normative drivers of the relative risk of wind versus water [distance to water (Q80) and building structure type (Q55)] and individual difference factors that might drive perceptions, including gender (Q86), education (Q75), age (Q72), ownership of a flood policy (Q60), and whether the respondent had previous experience living through a hurricane (Q63, and Q64). In this analysis the effect of distance was captured by four binary (indicator) variables that contrasted beliefs at each successive distance with those held by waterfront residents. The results of this analysis, reported in Table 2, supports only one marginally significant moderator of the tendency to believe that wind is the main threat posed by the storm—the respondent's age. Controlling for other factors, older respondents were more inclined to see wind as the greater risk over water. In contrast, there was no significant effect of increasing distance from a waterfront location, storm experience, housing type, or education or ownership of a flood policy. The absence of an effect of ownership of a flood policy would seem particularly surprising; even those who are sufficiently concerned about the threat of floods that they paid to insure against it believed that the greatest threat Sandy posed was from wind, not water.

Finally, there was also suggestive evidence that residents underestimated the likely *duration* of the

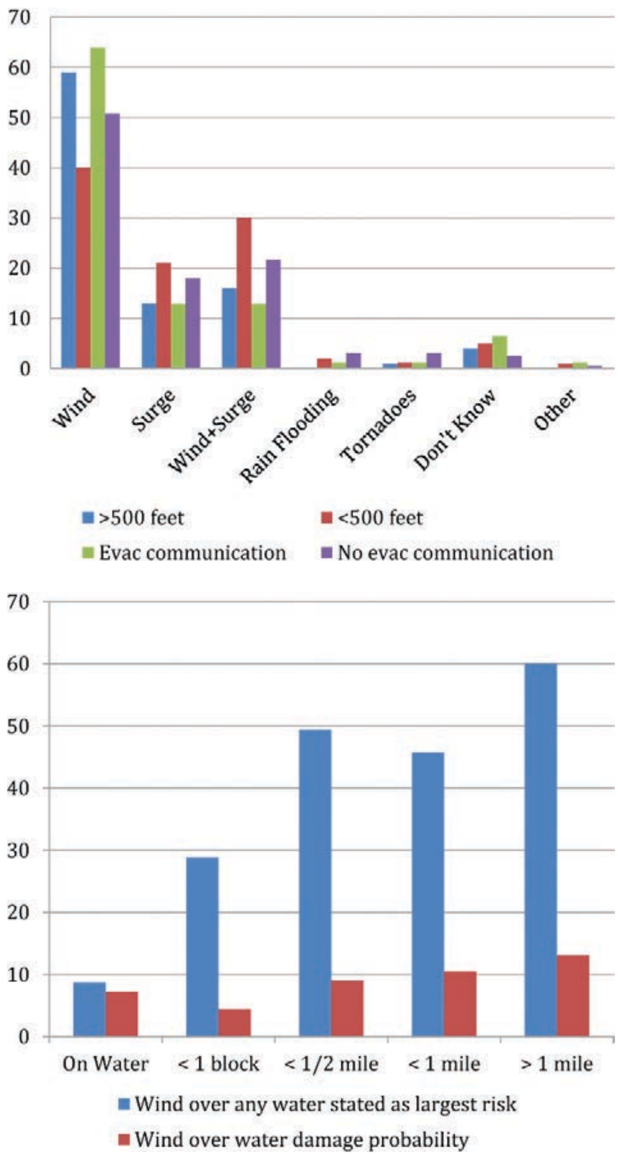

Fig. 5. (top) Beliefs about the greatest threat from Isaac by distance to coast. (bottom) Two different measures of beliefs of the threat of wind vs water from Sandy. Blue bars plot the difference in the percentage of respondents who identified wind as the greatest threat vs those who identified any one of three water threats. Red bars plot the difference in mean stated damage probability from wind minus that from water (stated maximum of either surge or rain).

impact of each storm. In our Sandy survey (though not for Isaac), we asked residents how long they expected to be without power during and after the hurricane (Q42). In Fig. 6 we plot the distribution of answers broken down by states where the path of the storm suggested the greatest impact would lie (New Jersey and Delaware) and where less of an impact was anticipated (Maryland and Virginia). The data suggest that residents were relatively optimistic about the duration of impact; the majority of residents thought either that, if they lost power, then it would be for less than 2 days (with 20% in all four states believing they would never lose power) or they held no belief about duration. In contrast, only 28% of coastal respondents in New Jersey and Delaware expected that they might be without power for more than 2 days—only slightly more than the expectations of residents in Maryland and Virginia (22%), where there would have been objective reasons to expect a smaller impact. What is notable about this optimism is that as Sandy approached, residents were widely warned to prepare for outages that could last 7–10 days, or the longest that had been experienced during Hurricane Irene the year before (see Lupkin 2012).[5] The optimistic beliefs, however, imply that many respondents either failed to hear such warnings or believed that if there were long outages, they were going to be experienced by people other than themselves.

Table 2. Regression of wind–water belief bias: Hurricane Sandy.

No. of observations	385
$F(8, 376)$	2.07
Prob > F	0.0382
R-squared	0.0404
RMSE	26.85

Predictor*	Estimate	Standard error	t value	Pr > t
Single-family home	5.163176	3.256452	1.59	0.114
Within 1 block of water	−5.710127	3.828923	−1.49	0.137
Within 1 mile of water	−5.827326	3.153236	−1.85	0.065
Have a separate flood policy	−4.323446	3.157173	−1.37	0.172
Education level	−1.492738	1.303257	−1.15	0.253
Age	2.219887	1.03686	2.14	0.033
Male	0.0377965	3.149295	0.01	0.990
Experienced hurricane in past	−2.603693	3.200698	−0.81	0.416
Constant	9.720106	7.77089	1.25	0.212

* Single family home = 1 for Q55 "detached single-family home," 0 otherwise (81% of the home type observations for Sandy are single-family detached homes); within 1 block of water = 1 for Q80 "directly on the water" and "within 1 block of water," 0 otherwise; within 1 mile of water = 1 for Q80 "within 1/2 mile of the water" and "within 1 mile of the water," 0 otherwise; over 1 mile of water = 1 for Q80 "more than 1 mile of the water," 0 otherwise and is the omitted dummy category. Have a separate flood policy = 1 for Q60 "yes," 0 otherwise; education level = Q75 discrete values 1–5; age = Q72 discrete values 1–6; male = 1 for Q86 "male," 0 otherwise. Experienced hurricane in past = 1 Q63 "yes" or Q64 "yes," 0 otherwise.

PROTECTIVE ACTIONS. *Short-term preparation.* Although respondents' beliefs about the threats posed by Isaac and Sandy differed in important ways from actual risks, an overwhelming proportion of respondents undertook at least some short-term preparatory action in advance of both storms, and almost all felt well prepared for the storms by the time that they arrived. The evolution of preparedness levels is depicted in Fig. 7, which plots the percentage of respondents for Isaac and Sandy (pooled) who indicated taking at least some preparatory action (Q37) and those who felt they were ready for the storm over time (Q40).

The data tell a clear and seemingly reassuring story: despite misperceptions that may have existed about how strong the winds would be at their homes and sources of danger, virtually all respondents took the storm seriously enough to undertake preparations—and to carry out these steps early. For example, when Sandy surveys began on the evening of 26 October—72 hours before the storm made landfall—over 75% of respondents had already taken some preparatory action, and by the time the storm

[5] The optimistic assessments of likely durations of power outages are consistent with those uncovered by Baker (2005a,b) in prestorm surveys among residents in Nassau and Suffolk Counties in Long Island, where only 4% of respondents in Nassau and 15% in Suffolk believed they would lose power for more than 2 days in the advent of a category 1 hurricane—the strength of Sandy.

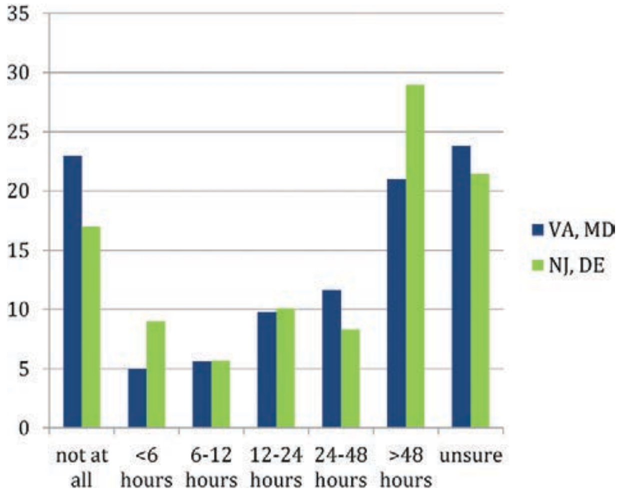

Fig. 6. Expected durations of power loss by state during Hurricane Sandy. The y axis reflects the percentage of respondents who indicated a given duration belief.

arrived on 29 October, over 94% felt sufficiently well prepared to endure whatever Sandy had to offer.

On the other hand, an analysis of the kind of preparations that were being taken provides a less encouraging view of readiness. In Fig. 8 we plot the time course of undertaking four major protective actions (Q37), pooling over storms: buying household supplies (e.g., groceries), putting up removable storm shutters (if owned), purchasing or readying a power generator, and developing an evacuation plan if needed (e.g., securing a hotel reservation).

The data show a disconcerting pattern of preparation: while the vast majority of respondents sought basic supplies in advance of each storm (6 h before landfall 88% reported doing so), more effortful actions were comparatively limited. For example, across time periods only 25% of respondents had made plans for where they would go if and an evacuation were ordered or needed, and in the last survey period when each storm was within 6 hours of predicted landfall less than 55% of residents who owned removable window protections (such as shutters) had put them up and 11% had secured or prepared electric generators.

Perhaps even more alarming was the observed limited compliance with evacuation advice. Though the survey methodology precluded us from directly measuring the percentage of respondents who actually complied with evacuation advice, it nevertheless provided two implicit measures: the change in the percentage of respondents who believed they were living in communities where evacuation had been advised yet who were still home to answer the survey as the time of landfall approached, and the change in the successful home contact rate (from Fig. 2). Because home telephones were randomly dialed, increasing actual evacuation rates over time should be mirrored by a decrease over time in the percentage of the sample of respondents who indicated that they were living in evacuation areas (or were home at all).

In Fig. 9 we plot the evolution of these implied compliance measures as well as stated intentions to leave among those respondents living in advised evacuation areas (from Q44, 49). Hurricane evacuation advisories are typically issued at least 36 hours before a storm's anticipated landfall, and, consistent with this practice, we see a sharp increase in awareness of evacuation warnings 30 hours before landfall. What is potentially disturbing, however, is that the data suggest that there was limited apparent compliance with this advice. Among those respondents who believed that they were living in communities where evacuations were ordered, the percentage who stated they intended to leave was, ironically, highest (55%) *before* a significant proportion indicated that they were aware that orders had been given (at 36 hours prior to landfall). Moreover, the percentage indicting intentions to leave decreased over time as awareness of orders grew. While we do not have direct measures of the percentage of actual compliance, further indications that the actual rate of evacuation was quite low is reflected by the absence of a decrease in the percentage of respondents living in evacuation areas who were home to answer the survey as the time of landfall approached. Specifically, 30 hours before landfall 54% of the respondents who were contacted said they were living in communities where evacuations had

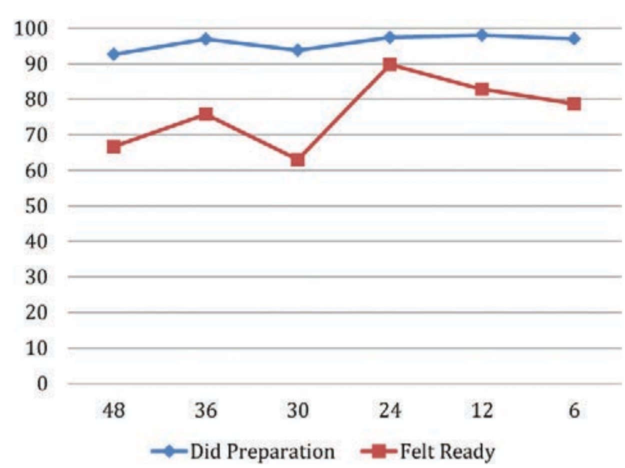

Fig. 7. Percentage of respondents who indicated taking some kind of protective action (blue line) and who felt that they had enough supplies on hand should the storm strike today (bottom line) in hours until landfall, pooled over storms.

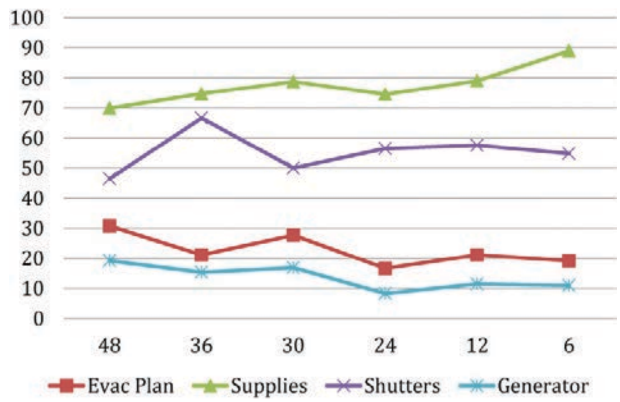

Fig. 8. Percentage of respondents taking different preparation actions as a function of hours until expected landfall, pooled over storms. "Evac plan" refers to making plans for where to go should evacuation be ordered or needed; "supplies" refers to purchased supplies for the home, such as food, water, and batteries; "shutters" refers to any removable window covering conditional on ownership; and "generator" refers to purchasing or readying a backup generator.

been advised. At 6 hours before landfall, however, this percentage remained almost the same—49%, a statistically negligible decrease that would be consistent with little, if any evacuation.

One possible explanation for the lack of intentions to take effortful actions is that residents believed that their particular homes were at limited risk of damage from either wind (for those who owned shutters) or flooding. To explore this, we analyzed the bivariate relationships that existed between the conditional likelihoods of installing shutters (given ownership; Q34, Q35, Q37) and evacuation intention (given living in an advised evacuation area; Q44, Q49) by respondents' beliefs about the probability that their homes would suffer damage from either winds (for shutters) or flooding (for evacuation). The data show only a weak association between the two constructs. For shutters, there was no significant relationship between shutter usage and subjective damage likelihood ($\chi^2 = .48$ (1, $N = 184$); $p > 0.1$). For example, 59% of those who believed that there was a greater than a 50–50 chance of experiencing wind damage to their homes ($N = 32$) put up their shutters, which was only nominally higher than that observed among people who believed that there was less than a 50–50 chance ($N = 152$; 52%). For evacuation there was a significant positive effect of risk beliefs on evacuation intentions ($\chi^2 = 8.44$ (1, $N = 284$); $p = 0.014$), but it was small in absolute terms; across all times periods and storms, 38% who thought that there was greater than a 50–50 chance of experiencing damage from rain or surge flooding ($N = 50$) expressed an intention to evacuate, compared to 20% among those who thought that there was less than a 50–50 chance ($N = 234$).

Long-term protection. The storm surveys also explored the degree to which residents had invested in long-term protection prior to Isaac and Sandy. This was either in the form of making improvements to their homes that would make them more resilient to damage from storms or owning flood insurance policies (Q65, Q59, Q60, respectively). The data suggest a troubling absence of such long-term investments in protection. Among respondents threatened by Sandy who had lived in their homes more than 11 years, only 17% reported having invested in storm-safety improvements in their homes (19% for all tenures). The percentages for Isaac were somewhat higher (38% for those in their homes more than 11 years, 35% overall), but they were still low considering frequent incidence of hurricanes along the central Gulf Coast.

Ownership of federal flood policies was also limited. For example, in areas threatened by Sandy, only 53% of those living within a half mile (0.8 km) of water (bay or ocean) indicated that they owned flood policies (54%, including those who were uncertain whether the coverage was separate from the regular homeowners' policy), with this percentage only slightly higher (57%; 59% adjusted for uncertainty)

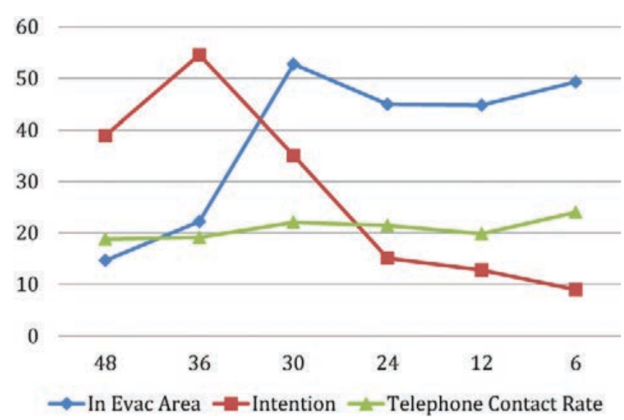

Fig. 9. Intended and inferred actual measures of evacuation for the last 48 hours prior to landfall, pooled over storms. Blue line (with diamond symbols) is the percentage (y axis) of respondents living in communities where evacuation had been advised who stated an intention to leave (percentage intention given awareness). Red line (with square symbols) is the percentage of respondents who indicated that they were living in an evacuation area (percentage aware). Green line (with triangle symbols) is the percentage of the pooled at-home successful contact rate (pooled from Fig. 2).

among those who indicated living within one block of water. In areas threatened by Isaac, ownership of flood policies among those living in proximity of water was higher but still far from complete; among those living within a half mile of open water, only 70% indicated that they had purchased a federal flood policy. Although this incidence of flood insurance purchase might seem to be acceptable, it is certainly lower than desirable,

What explains the low ownership of flood policies among those at high risk from flood? One contributing mechanism may have been a mistaken belief among residents that their regular homeowners' policies covered them for flood losses. Specifically, across our whole sample, among the 42% who expressed the belief that they were insured against flood losses, only 51% indicated that they own a separate federal flood policy, with 3% being unsure. This implies that potentially half of the respondents who thought that they were covered in the event of a flood loss were, in fact, not.

DISCUSSION. One of the greatest challenges facing forecasters and emergency management officials worldwide is to design natural-hazard communication strategies that successfully encourage individuals in threatened areas to take appropriate protective actions—both in their responses to immediate threats as well as their long-term decisions about housing and personal risk management (Morss et al. 2010; Demuth et al. 2012). The enormous property losses that have occurred as a result of tropical cyclones in recent years, however, suggest that communication efforts have not been as effective as they might be. Individuals living in areas prone to flood risk have been found to chronically underinsure (e.g., Kousky and Michel-Kerjan 2012), and individuals fail to evacuate in the face of explicit warnings when faced with hurricane risks (Baker 1991; Huang et al. 2012).

What makes this problem particularly vexing in the case of tropical cyclone threats is that in recent years researchers have witnessed large gains in public awareness of these storms. When hurricanes approach coastlines in the United States, they are major media events; in our work, not a single respondent was unaware that his location was threatened either by Hurricane Isaac or Sandy, and the vast majority of respondents reported keeping regularly abreast of the latest storm news as each storm approached, with over 80% of respondents indicating their latest information was less than 2 hours old. Yet somehow this ubiquitous awareness did not translate into uniformly appropriate protective actions; only 55% of the respondents that we sampled whose homes were equipped with removable window protection installed it as the storms approached, and only a small proportion of those who believed that they were living in areas where evacuations had been advised expressed an intention to leave; we had no problem finding residents in evacuation areas at home to answer their phones as each storm approached.

The goal of this research was to complement earlier attempts to better understand the factors that underlie decisions to undertake protective action in the face of hurricane threats by reporting the findings of two "real time" surveys of coastal residents as hurricanes Isaac and Sandy approached the United States in 2012. The data provide the first look at how hurricane threat perceptions evolve over time in response to warnings as storms approach the coast, and how protective decisions are being made when the storm's outcome is still in doubt.

The findings provide what might be seen as a disquieting—and in some cases paradoxical—view of hurricane threat perceptions and response. As noted above there was universally high awareness about the threat posed by Isaac and Sandy as each approached the coast, but there also was evidence that residents held poor mental models of both the nature and duration of the personal impacts that the storms could have. One of the surprising results was that individuals overestimated the probability that their locations would be impacted by winds of hurricane force (75 mph or more) compared to scientific estimates provided by the National Hurricane Center, yet this pessimism did not translate to correspondingly high degrees of concern about the damage that such winds might cause or induce residents to take the kind of protective actions that such beliefs would seem to warrant. Only a fraction of those owning removable storm shutters put them up, few secured backup generators in anticipation of long power outages, and roughly only 20% made evacuation plans should they be needed.

There was also little evidence in the data that preparation was inhibited by social pressures, by beliefs that certain measures would be ineffective, or by barriers to undertaking them (Lindell and Pratter 2012). For example, when respondents who were aware they were living in evacuation areas were asked why they did not intend to leave (Q53), only 1% cited physical limitations, 1% cited that they were advised to stay by friends or relatives, and 7% cited that they desired to protect their homes. The most common reason was a belief that there was simply no need to; 75% indicated that they felt safe staying put.

Were these feelings of safety misplaced? One of the major findings of our work was that many residents misconstrued the primary *locus* of the threat posed by hurricanes as coming from wind rather than water. This is a bias, we should note, that has been observed in other contexts. For example, in surveys among Texas residents after Hurricanes Lili, Bret, and Rita, Lindell and Prater (2008), found that coastal residents similarly underestimated the risks posed by storm surge relative to wind, and concern about wind damage was more strongly associated with intentions to evacuate from future storms. Likewise, an excessive focus on wind rather than flooding risk was been cited as a major cause of lives lost in France during Cyclone Xynthia in February 2010 (Vinet et al. 2012). What was particularly notable was that we observed the tendency to underestimate the relative threat posed by water in Isaac and Sandy even among those for whom the threat should have been most salient; for example, in our Sandy survey, even people having waterfront properties and who held flood insurance policies felt that there was a higher probability that their homes would suffer damage from wind than flooding.

While the forces that gave rise to these poor mental models are uncertain, we can offer some speculations. First, some of the findings might be explained by endemic biases in how people perceive and respond to risk that have been observed in other contexts. For example, it has long been observed that when responding to hazards—be they natural, health, or man made—people are prone to believe that they will be less likely to suffer harm than others—an effect termed the optimistic bias (Shepperd et al. 2013; Trumbo et al. 2011; Weinstein 1980). The optimistic bias provides a natural explanation for why residents might display upwardly biased beliefs that the storms would bring hurricane-force winds to their locations but then express limited concern that such winds would cause personal harm.

But while inherent optimism might explain some aspects of the data, we suggest that other observed biases may have their root in how the risks of hurricanes are often communicated to residents. For example, one factor that would seem likely to contribute to an overweighing of wind over water risk is that that storm intensity is currently exclusively conveyed by National Oceanic and Atmospheric Administration (NOAA) by the Saffir–Simpson scale, which describes the maximum sustained winds that a storm possesses, not its maximum storm surge or flood threat. While the National Hurricane Center made clear efforts to warn residents of flood risk of each storm, our surveys revealed that residents nevertheless had a higher awareness of a storm's maximum winds rather than flood potential. Specifically, when respondents were asked to report what they believed Isaac's and Sandy's maximum winds and predicted maximum storm surges to be, respondents were much better at the former than the latter; whereas 88% of respondents in Isaac and 79% in Sandy could recall the wind forecast (Q7), only 67% in Isaac and 63% in Sandy could recall the storm surge forecast (Q9). Simple greater mental availability of the wind threat could explain at least some of the bias.

Another likely contributing factor is that in many cases wind damage is inherently easier to mentally simulate than flooding damage (Meyer 2006). Whereas we experience (modestly) high winds and see its consequences on a regular basis, flood events are rare. Mental simulation of flood losses would be particularly difficult for individuals whose homes are not in beachfront locations, where surge risks might easily be imagined. A New York resident living in a high-rise building in lower Manhattan during Sandy might thus be forgiven for overlooking "storm-surge risk" as a major personal threat, when, in fact, it was the greatest threat faced during the storm due to flooding, which could prohibit escape from the building and make the building uninhabitable for long periods.

What might be done to improve residents' mental models of tropical cyclone threats? As a starting point, the findings of this work strongly support recent calls for hurricane communication to focus less on a hurricane's maximum wind strength (which is typically found in small areas near the center) and more on the impacts that residents living in different areas are likely to experience, particularly with respect to flood (e.g., Demuth et al. 2012; Huang et al. 2012), or other attributes of a hurricane's wind field, such as size, duration, or directional uniformity (Czajkowski and Done 2013). Achieving this goal, however, is unlikely to be easy, as it will almost certainly require more than emphasizing flood risks in advisories and disseminating flood-risk maps to residents. As Hurricane Isaac approached the Louisiana coast, for example, the National Hurricane Center's advisories emphasized flooding (from surge and rain) as the primary threat posed by the storm (e.g., advisory 28, 27 August), and in Sandy the advisory headlines similarly emphasized surge risks. Likewise, residents cannot be assumed to develop better intuitions simply by providing better maps and evacuation-education programs before storms; prior research suggests that many residents do not know their evacuation zones, even when aided by a map (e.g., Baker 2005a,b; Arlikatti et al. 2006; Zhang et al. 2004).

Hence, if there is to be a solution, it will likely require an orchestrated suite of communication activities that characterize the strength of a storm in terms of both its size and nature of impacts, rather than just wind strength. For example, the Met Office has recently experimented with the use of color-coded "risk grids" that simultaneously convey the probability and severity of storm impacts (Demeritt 2012), and Morss et al. (2010) provide further support for the ability of individuals to utilize probabilistic forecasts.

Likewise, officials could consider exploring tools that would allow residents to more easily mentally simulate *how* storms could induce damage. To illustrate, in Sandy one of the greatest sources of personal property losses was from private automobiles—a loss that could easily have been avoided had residents simply known the damage that flood waters can do to a car and move them out of harm's way as the storm was approaching.

Of course, there are likely strong limits to what better education and more targeted communication might hope to achieve. In many cases the greatest source of decision errors in the face of hazards is that individuals are uncertain about the correct course of action and end up choosing familiar default options that are decidedly suboptimal for a given situation—such as choosing to stay when one is unsure whether to evacuate or, in the tragic case of Hurricane Sandy, choosing to evacuate by taking a familiar road that goes through an unmarked surge zone (Koplowitz 2012).

In this case we follow Thaler and Sunstein (2008) and others by suggesting that communities work to develop stronger sets of "decision defaults" that reduce the uncertainty that typically accompany individual decisions about when and how much to prepare. For example, Kunreuther and Michel-Kerjan (2009) have argued in support of long-term flood insurance contracts that have automatic annual decisions about renewal. Similar mechanisms could be extended to short-term preparedness, such as communities developing a program that annually distributes hurricane kits to all residents from which households can opt out—shifting the focus of decision making from that of whether one should prepare to whether one should *not* prepare.

Finally, our hope is that this research will spawn additional attempts to conduct real-time measurement of responses to natural hazards. The technical challenges of doing such work, however, are formidable. One of the limitations of relying on landlines as used here that we noted at the outset is the risk of sample-selection bias as storms approach; those who are more concerned with risk will be more likely to evacuate their homes, possibly resulting in a biased view of actual intended evacuation and storm preparation levels. While we offered evidence that in the case of Isaac and Sandy there was little sample attrition (e.g., home contact rates on the last day were not significantly different than the first), this cannot be expected to be the case in general given more severe storms. Likewise, another source of bias is the fact that wireless phones are increasingly replacing landlines as the major telecommunication channel used by households, particularly those who are younger [in 2012 the Centers for Disease Control and Prevention (CDC) estimated that 34% of U.S. households have only wireless phone service; Blumberg and Luke 2012].

As such, consideration needs to be given to alternative contact methods, such as brief surveys delivered to smart phones. Those methods, however, will have their own challenges, at least at this point in time. Aside from the pragmatic difficulties of implementing surveys on mobile phones [which are partially restricted under the Telemarketing Consumer Protection Act (TCPA) of 1991[6]], there would be a loss of precise locational information, which is critical if one hopes to map risk perceptions to objective risk. One possibility might be to integrate real-time surveys into weather- and protection-related smartphone apps where respondents give prior consent to responding to brief surveys and surrendering GPS location information. Such an approach might allow future research not just to replicate the work reported here but also investigate spatial dynamics, such as movement after warnings have been issued.

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[6] The TCPA allows surveys to be conducted on cell phone numbers as long as they are manually dialed. Even in such cases, rates of compliance may be affected because it may be the responsibility of the recipient to pay for incoming call time.

REFERENCES

Arlikatti, S., M. K. Lindell, C. S. Prater, and Y. Zhang, 2006: Risk area accuracy and hurricane evacuation expectations of coastal residents. *Environ. Behav.,* **38,** 226–247, doi:10.1177/0013916505277603.

Avila, L. A., and J. Cangialosi, cited 2011: Tropical cyclone report: Hurricane Irene. National Hurricane Center, 45 pp. [Available online at www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf.]

Baker, E. J., 1991: Hurricane evacuation behavior. *Int. J. Mass Emerg. Disasters,* **9,** 287–310.

——, 2005a: Nassau County hurricane evacuation behavioral survey. Report prepared for the U.S. Corps of Engineers.

——, 2005b: Suffolk County hurricane evacuation behavioral survey. Report prepared for the U.S. Corps of Engineers.

Berg, R., 2012: Tropical cyclone report: Hurricane Isaac (AL092012). National Hurricane Center, 78 pp. [Available online at www.nhc.noaa.gov/data/tcr/AL092012_Isaac.pdf.]

Bibel, S., cited 2012: The Weather Channel's Hurricane Sandy coverage garners the network's highest-ever ratings. [Available online at http://tvbythenumbers.zap2it.com/2012/10/30/the-weather-channel-s-hurricane-sandy-coverage-garners-the-networks-highest-ever-ratings/155312/.]

Blake, E. S., C. W. Landsea, and E. J. Gibney, 2011: The deadliest, costliest, and most intense tropical cyclones from 1851 to 2010 (and other frequently requested hurricane facts). NOAA Tech. Memo. NWS NHC-6, 47 pp. [Available online at www.nhc.noaa.gov/pdf/nws-nhc-6.pdf.]

——, T. B. Kimberlain, R. J. Berg, J. P. Cangialosi, and J. L. Beven II, 2013: Tropical cyclone report: Hurricane Sandy (AL182012). NOAA Rep., 157 pp. [Available online at www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf.]

Blumberg, S. J., and J. V. Luke, 2012: Wireless substitution: Early release of estimates from the National Health Interview Survey, January–June 2012. Division of Health Interview Statistics, National Center for Health Statistics, Centers for Disease Control and Prevention, 19 pp. [Available online at www.cdc.gov/nchs/data/nhis/earlyrelease/wireless201212.pdf.]

Broad, K., A. Leiserowitz, J. Weinkle, and M. Steketee, 2007: Misinterpretations of the "cone of uncertainty" in Florida during the 2004 hurricane season. *Bull. Amer. Meteor. Soc.,* **88,** 651–667, doi:10.1175/BAMS-88-5-651.

Brown, R. S., C. W. Williams, and P. R. Lees-Haley, 1994: The effects of hindsight bias on causal attribution on human response to natural events. *J. Appl. Soc. Psychol.,* **24,** 661–674, doi:10.1111/j.1559-1816.1994.tb00606.x.

Cangialosi, J. P., and J. L. Franklin, 2013: 2012 National Hurricane Center forecast verification report. NOAA National Hurricane Center Tech. Rep., 79 pp. [Available online at www.nhc.noaa.gov/verification/pdfs/Verification_2012.pdf.]

Czajkowski, J., and J. Done, 2013: As the wind blows? Understanding hurricane damages at the local level through a case study analysis. *Wea. Climate Soc.,* **6,** 202–217, doi:10.1175/WCAS-D-13-00024.1.

Dash, N., and H. Gladwin, 2007: Evacuation decision making and behavioral responses: Individual and household. *Nat. Hazards Rev.,* **8,** 69–77, doi:10.1061/(ASCE)1527-6988(2007)8:3(69).

Demeritt, D., 2012: The perception and use of public weather services by emergency and resiliency professionals in the UK. Report for the Met Office Public Weather Service Customer Group, 38 pp. [Available online at www.kcl.ac.uk/sspp/departments/geography/people/academic/demeritt/DemerittPWSCGreport02032012FINAL.pdf.]

Demuth, J. L., R. E. Morss, B. H. Morrow, and J. K. Lazo, 2012: Creation and communication of hurricane risk information. *Bull. Amer. Meteor. Soc.,* **93,** 1133–1145, doi:10.1175/BAMS-D-11-00150.1.

Dow, K., and S. L. Cutter, 1998: Crying wolf: Repeat responses to hurricane evacuation orders. *Coastal Manage.,* **26,** 237–252, doi:10.1080/08920759809362356.

Fischhoff, B., and R. Beyth, 1975: I knew it would happen: Remembered probabilities of once—Future things. *Organ. Behav. Hum. Perform.,* **13,** 1–16, doi:10.1016/0030-5073(75)90002-1.

Gall, R., J. Franklin, F. Marks, E. N. Rappaport, and F. Toepfer, 2013: The Hurricane Forecast Improvement Project. *Bull. Amer. Meteor. Soc.,* **94,** 329–343, doi:10.1175/BAMS-D-12-00071.1.

Huang, S.-K., M. J. Lindell, C. Prater, H.-C. Wu, and L. K. Siebeneck, 2012: Household evacuation decision making in response to Hurricane Ike. *Nat. Hazards Rev.,* **13,** 283–296, doi:10.1061/(ASCE)NH.1527-6996.0000074.

Jones, N. A., H. Ross, T. Lynam, P. Perez, and A. Leitch, 2011: Mental models: An interdisciplinary synthesis of theory and methods. Ecol. Soc., 16, (46). [Available online at www.ecologyandsociety.org/vol16/iss1/art46/.]

Koplowitz, H., 2012: Glenda Moore, Staten Island mother who lost 2 sons in Hurricane Sandy, returns to site of tragedy. [Available online at www.ibtimes.com/glenda-moore-staten-island-mother-who-lost-2-sons-hurricane-sandy-returns-site-tragedy-858289.]

Kousky, C., and E. Michel-Kerjan, 2012: *Hurricane Sandy's storm surge and the NFIP: Flood insurance coverage in New York and New Jersey.* Wharton Center for Risk Management and Decision Processes Issue Brief, 4 pp. [Available online at http://opim.wharton.upenn.edu/risk/library/WRCib2012c_Sandy-and-the-NFIP.pdf.]

Kunreuther, H. C., and E. O. Michel-Kerjan, 2009: *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes.* MIT Press, 464 pp.

Lindell, M. K., and C. S. Prater, 2008: Behavioral analysis: Texas evacuation study. Texas A&M University Hazard Reduction and Recovery Center Tech. Rep.

—— and ——, 2012: The Protective Action Decision Model: Theoretical modifications and additional evidence. *Risk Anal.,* **32,** 616–632, doi:10.1111/j.1539-6924.2011.01647.x.

——, J.-C. Lu, and C. S. Prater, 2005: Household decision making and evacuation in response to Hurricane Lili. *Nat. Hazards Rev.,* **6,** 171–179, doi:10.1061/(ASCE)1527-6988(2005)6:4(171).

Lupkin, S., 2012: Hurricane Sandy: New Jersey warned of 7- to 10-day power outages. [Available online at http://abcnews.go.com/US/hurricane-sandy-jersey-prepares-10-day-power-outages/story?id=17579827#.UZVdQbWR-O0.]

Meyer, R. J., 2006: Why we underprepare for hazards. *On Risk and Disaster: Lessons from Hurricane Katrina,* R. J. Daniels, D. F. Kettl, and H. Kunreuther, Eds., University of Pennsylvania Press, 153–174.

Morss, R. E., and M. H. Hayden, 2010: Storm surge and “certain death”: Interviews with Texas coastal residents following Hurricane Ike. *Wea. Climate Soc.,* **2,** 174–189, doi:10.1175/2010WCAS1041.1.

——, J. K. Lazo, and J. L. Demuth, 2010: Examining the use of weather forecasts in decision scenarios: Results from a US survey with implications for uncertainty communication. *Meteor. Appl.,* **17,** 149–162, doi:10.1002/met.196.

Neisser, U., E. Winograd, E. T. Bergman, C. A. Schreiber, S. E. Palmer, and W. S. Weldon, 1996: Remembering the earthquake: Direct experience vs. hearing the news. *Memory,* **4,** 337–358, doi:10.1080/096582196388898.

Norris, F. H., and K. Kaniasty, 1992: Reliability of delayed self-reports in disaster research. *J. Trauma. Stress,* **5,** 575–588, doi:10.1002/jts.2490050407.

National Weather Service, cited 2012: Hurricane Sandy advisory number 26. [Available online at www.nhc.noaa.gov/archive/2012/al18/al182012.public.026.shtml.]

Peacock, W. G., S. D. Brody, and Wes Highfield, 2005: Hurricane risk perceptions among Florida’s single family homeowners. *Landscape Urban Plann.,* **73,** 120–135, doi:10.1016/j.landurbplan.2004.11.004.

Pew Research Center, 2012: Assessing the representativeness of public opinion surveys. Pew Research Center Rep., 51 pp. [Available online at www.people-press.org/files/legacy-pdf/Assessing%20the%20Representativeness%20of%20Public%20Opinion%20Surveys.pdf.]

Pielke, R. A., Jr., cited 2012: Updated: Normalized hurricane damage 1900–2012. [Available online at http://rogerpielkejr.blogspot.com/2012/12/updated-normalized-hurricane-losses.html.]

——, J. Gratz, C. W. Landsea, D. Collins, M. A. Saunders, and R. Musulin, 2008: Normalized hurricane damage in the United States: 1900–2005. *Nat. Hazards Rev.,* **9,** 29–42, doi:10.1061/(ASCE)1527-6988(2008)9:1(29).

Shepperd, J. A., W. M. P. Klein, E. A. Waters, and N. D. Weinstein, 2013: Taking stock of unrealistic optimism. *Perspect. Psychol. Sci.,* **8,** 395–411, doi:10.1177/1745691613485247.

Taylor, A., 2013: Hurricane Sandy: 80 days later. [Available online at www.theatlantic.com/infocus/2013/01/hurricane-sandy-80-days-later/100440.]

Thaler, R. H., and C. R. Sunstein, 2008: *Nudge: Improving Decisions about Health, Wealth, and Happiness.* Yale University Press, 320 pp.

Trumbo, C., M. Lueck, H. Marlatt, and L. Peek, 2011: The effect of proximity to Hurricanes Katrina and Rita on subsequent hurricane outlook and optimistic bias. *Risk Anal.,* **31,** 1907–1918, doi:10.1111/j.1539-6924.2011.01633.x.

Vinet, F., D. Lumbroso, S. Defossez, and L. Boissier, 2012: A comparative analysis of the loss of life during two recent floods in France: The sea surge caused by the storm Xynthia and the flash flood in Var. *Nat. Hazards,* **61,** 1179–1201, doi:10.1007/s11069-011-9975-5.

Weinstein, N., 1980: Unrealistic optimism about future life events. *J. Pers. Soc. Psychol.,* **39,** 806–820, doi:10.1037/0022-3514.39.5.806.

Zhang, F., and Coauthors, 2007: An in-person survey investigating public perceptions of and responses to Hurricane Rita forecasts along the Texas coast. *Wea. Forecasting,* **22,** 1177–1190, doi:10.1175/2007WAF2006118.1.

Zhang, Y., C. S. Prater, and M. K. Lindell, 2004: Risk area accuracy and evacuation from Hurricane Bret. *Nat. Hazards Rev.,* **5,** 115–120, doi:10.1061/(ASCE)1527-6988(2004)5:3(115).

IMPACT OF TYPHOONS ON THE OCEAN IN THE PACIFIC

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The interactions between typhoons and the ocean vary greatly depending on the properties of the storm and of the ocean.

Tropical cyclones (TCs) interact with both the atmosphere and the upper ocean. They draw their energy from the warm ocean, but in doing so also change the ocean in a broad swath around their track by direct cooling and through the action of the ocean waves and currents generated by TC winds (Leipper 1967; Price 1981; Black 1983; Shay 2010; and references therein). This affects the evolution of the TC and also leaves an imprint on the ocean that can last long after the storm has passed. The Impact of Typhoons on the Ocean in the Pacific/Tropical Cyclone Structure 2010 (ITOP/TCS10) program combined intensive meteorological and oceanographic observations of TCs in the western North Pacific to study these interactions and compare them to previous measurements in the Atlantic (e.g., Black et al. 2007) and Gulf of Mexico (e.g., Jaimes and Shay 2009, 2010)

ITOP GOALS. *How does the cold wake of a typhoon form and dissipate?* Typhoons produce a complex three-dimensional response in the underlying ocean including strong mixed layer currents, upwelling of the thermocline, intense mixing across the thermocline, generation and propagation of near-inertial internal waves, and the formation of a cold wake beneath the storm. The cold wake persists after the typhoon passage (Pudov and Petrichenko 2000), modifying the air–sea interaction and the biogeochemistry of the upper ocean (Shay 2010; Lévy et al. 2012; and references therein), and decaying through a poorly known combination of air–sea flux and

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mixing processes. Although previous observations have shown cold wakes reappearing in SST observations after a period of warming (e.g., Price et al. 2008), detailed observations of this phenomenon are rare, with subsurface observations mostly focusing on the first few days of evolution.

ITOP aimed to measure the ocean response to typhoons in detail, particularly the formation and dissipation of the cold wake, and to compare these measurements with the predictions generated by numerical models.

What are the air–sea fluxes for winds greater than 30 m s⁻¹? TCs draw their energy from the underlying warm ocean and thus tend to be more intense if the fluxes of heat and moisture from the ocean are greater (Emanuel 1999). They are damped by drag on the ocean and thus tend to be less intense if the drag is greater. Although the drag coefficient is now believed to remain constant or decrease at high wind speeds (Black et al. 2007), large uncertainties among different observations and parameterizations of momentum, heat, and moisture exchange rates remain. ITOP aimed to make additional measurements, at higher wind speeds, and under a larger variety of atmospheric and oceanic conditions.

How does the ocean stratification and its variability affect the ocean response to typhoons? Variability in the ocean thermal structure due to regional differences and to transient variations caused by ocean eddies is expected to modify the air–sea fluxes and thus TC intensity. Regions with warm, deep upper layers may act as typhoon boosters by limiting the amount of cooling beneath the storm, and those with cold, shallow upper layers correspondingly act as typhoon dampers (e.g., Hong et al. 2000; Lin et al. 2005, 2008). Eddy currents may complicate these interactions (Yablonsky and Ginis 2013). We expect eddy effects to be stronger in the western Pacific than in the Atlantic because the typical sea surface height variability in the western Pacific is 50%–100% larger than in the open western Atlantic. ITOP aimed to study these interactions in detail.

How do surface waves affect air–sea interactions beneath typhoons? Surface wave fields beneath typhoons are complex, with multiple dominant wave directions varying and interacting across the different storm quadrants (Wright et al. 2001). The new generation of coupled TC models includes explicit wave fields from which the air–sea heat and momentum fluxes are computed (Chen et al. 2007, 2013). More practically, the surface waves produced by typhoons are of great interest in themselves, especially relevant in marine and impact forecasting. ITOP aimed to measure the surface wave field underneath typhoons, to compare these measurements with models, and to assess their impact on air–sea exchange and remote sensing signatures.

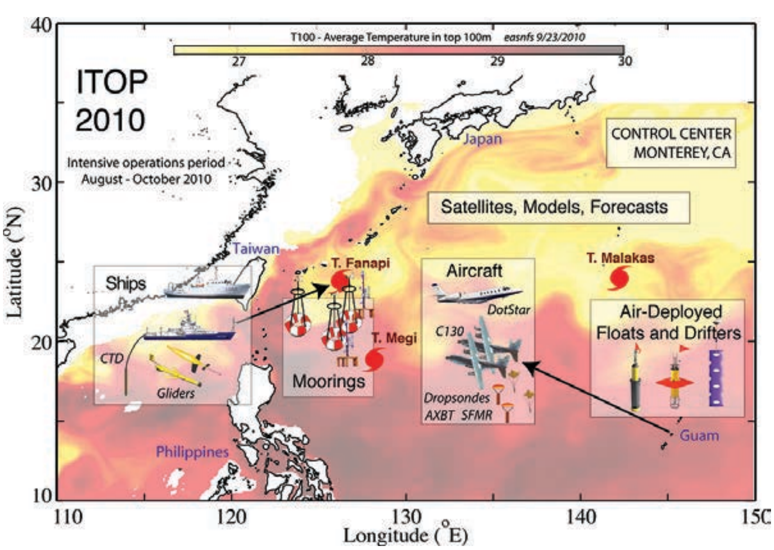


Fig. 1. Background color map of T100, the average temperature in the upper 100 m of the ocean, from the East Asia Seas Nowcast/Forecast System on 23 Sep 2010. Overlaid are graphical representations of the ITOP operations area, experimental tools, and strategy. Locations of the three major ITOP storms at the time of maximum sampling are shown by storm symbols.

EXPERIMENTAL SETTING, TOOLS, AND STRATEGY. The experiment focused on the western tropical North Pacific, a region with the highest climatological density of typhoons. This region has strong north–south gradients in ocean stratification (Fig. 1) but not SST (Fig. 2). The average temperature in the upper 100 m of the ocean (T100) is a simple estimate of the expected surface temperature after typhoon mixing (Price 2009). In the south, T100 averages 30°C, only about 0.5°C less than the surface temperature before typhoon mixing; here, mixing by typhoons will cause very little ocean cooling and will have little effect on the air–sea temperature difference during TCs. In the north, T100 reaches 26°C, about 3.5°C less than the surface temperature before typhoon mixing; here typhoon-induced mixing will cause strong ocean cooling and is more likely to reduce the air–sea temperature difference beneath TCs. Between roughly 19° and 22°N T100, and thus the ocean feedback to TCs, is highly variable due to strong ocean eddies (Lin et al. 2005, 2008).

The ITOP experimental strategy used both traditional and newly developed tools to sample oceanic and atmospheric variability on a variety of space and time scales (Fig. 1). During an intensive observation period (August–October 2010), detailed measurements of typhoons and the immediate ocean response were made using aircraft. Two WC-130J "Hurricane Hunter" aircraft were operated by the Air Force Reserve Command 53rd Weather Reconnaissance Squadron from Guam, and an Astra jet aircraft was operated by the Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) program (Wu et al. 2005). The WC-130s penetrated the storms during reconnaissance flights, observing their structure and that of the underlying ocean. Dropsondes measured wind, air temperature, and humidity; a microwave sensor, the Stepped Frequency Microwave Radiometer (SFMR; Uhlhorn et al. 2007), measured surface wind and rainfall; and airborne expendable bathythermographs (AXBTs) measured the ocean temperature in the upper 500–800 m. The Astra conducted surveillance flights in the environment around storms approaching Taiwan using dropsondes. More detailed and extended measurements of the ocean and of the atmospheric boundary layer were made using a new generation of autonomous oceanographic instruments developed during the Coupled Boundary Layer Air–Sea Transfer (CBLAST) program (Black et al. 2007). A total of 81 Electromagnetic Autonomous Profiling Explorer (EM-APEX) floats (Sanford et al. 2011), Lagrangian floats (D'Asaro and McNeil 2007), and several varieties of surface drifters (Niiler 2001; Black et al. 2007; Centurioni 2010) were deployed in specially designed air-launch packages from a WC-130 aircraft. Arrays of these instruments were deployed in front of typhoons Fanapi and Megi and measured the evolution of ocean temperature, salinity, and velocity through each storm's passage and for longer than one month afterward. Some instruments also measured surface pressure, surface waves, and ocean boundary layer turbulence. Additional instruments deployed after the passage of typhoons Fanapi and Malakas measured the long-term evolution of the storm wakes.

A longer-term context was provided by moorings deployed off Taiwan from March 2009 to November 2010 (Pun et al. 2011). Four surface buoy moorings and three subsurface moorings measured surface meteorology and ocean structure in the upper 500 m. During the intensive observation period, these moorings were supplemented by two highly instrumented, tandem air–sea interaction and surface wave moorings, combining a robust surface platform [the Extreme Air–Sea Interaction (EASI) buoy] with a spar buoy [the Air–Sea Interaction Spar (ASIS)] (Graber et al. 2000). The moored array measured the response to four storms.

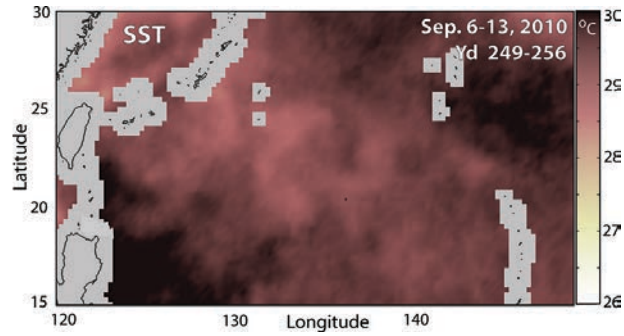


Fig. 2. Mean sea surface temperature, 6–13 Sep 2010, just before the genesis of Typhoon Fanapi. Color scale is as in Fig. 1, demonstrating the lack of SST contrast. Data from the Optimally Interpolated (OI) SST product produced by Remote Sensing Systems.

The research vessels *Revelle, Ocean Researcher 1,* and *Ocean Researcher 3* were used to deploy and recover the moorings and to study the evolution of the storm wakes on time scales of days to many weeks. During the intensive observation period R/V *Revelle* was initially poised near Taiwan conducting other research and was mobilized rapidly as ITOP's first storm, Typhoon Fanapi, formed. The R/V *Revelle* made detailed surveys of the wakes of Fanapi and Megi and deployed 10 autonomous gliders (Eriksen et al. 2001) to measure ocean temperature and salinity and ocean mixing rates and conducted studies of the biogeochemical properties of the wake. The gliders continued surveying the wake for another 50 days. Gliders, floats, some drifters, and the moorings were recovered by the research vessels after the end of the intensive period.

Synthetic aperture radar (SAR) images from seven satellites (including *Envisat*, *TerraSAR-X*, *COSMO-SkyMed*, and *RadarSat-2*) provided coverage of the typhoons in different stages of development. Close cooperation between the ITOP Operations Center and the Center for Southeastern Tropical Advanced Remote Sensing (CSTARS), the satellite downlink facility, resulted in multiple eye images of all three ITOP storms. SAR satellite data were used to generate

Table 1. ITOP tropical cyclone properties. Inner core structure parameters of eyewall slope and slant reduction factor are averaged over all passes through the core during an aircraft mission near the time of maximum intensity (with maximum wind tilt angle from vertical in parentheses).

Storm ID	12W	13W	15W
Storm name	Typhoon Fanapi	Typhoon Malakas	Supertyphoon Megi
Mission IDs	0420–0620	0222–0422	0330–0830
ITOP observation period (2010)	14–20 Sep	20–25 Sep	13–23 Oct
Maximum SFMR surface wind (kt)	115	90	183
Average flight level R_{max} (nm)	22	45	9
Minimum pressure (mb)	930	948	890
Average ratio: R_{max} sfc to R_{max} 700 mb	0.81 ± 0.09	0.72 ± 0.14	0.94 ± 0.14
V_{max} slope/tilt (°)	0.39 (79)	0.13 (83)	1.85 (46)
Average slant reduction ratio: V_{max} sfc to V_{max} 700 mb	0.88 ± 0.07	0.80 ± 0.20	0.92 ± 0.04

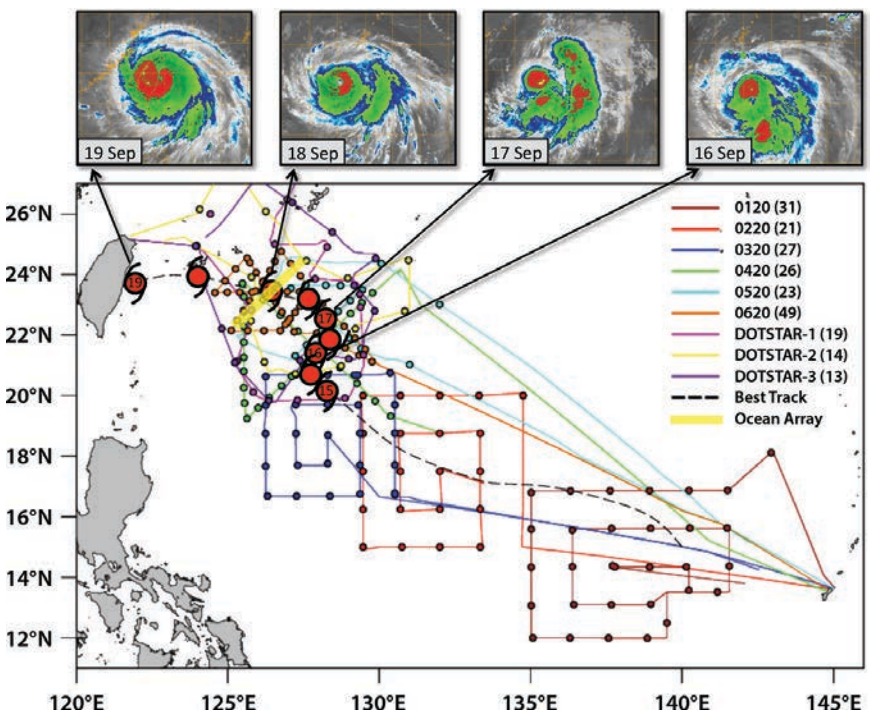


Fig. 3. Aircraft flight tracks and the best track of Typhoon Fanapi. Each WC-130J aircraft mission is defined as xx20, where xx is the mission number and 20 represents the ITOP reference number for the pre-Fanapi disturbance. The DOTSTAR missions are labeled sequentially. The number in parentheses following each aircraft mission label defines the number of dropwindsondes deployed during the mission. The dropwindsonde deployment locations are defined by the circles along each flight track. The dashed line defines the track of the pre-Fanapi disturbance (www.usno.navy.mil/JTWC/). Tropical cyclone symbols begin at the time that the tropical cyclone reached tropical storm intensity and are placed at 12-h intervals. A Multi-functional Transport Satellite (MTSAT; Japan Meteorological Agency) infrared image is provided at each 0000 UTC time. A yellow line shows the deployment line of oceanographic floats and drifters.

high-resolution wind fields (Horstmann et al. 2000, 2005, 2013; Romeiser et al. 2013; Wackerman et al. 1996), surface pressure fields using the method described by Patoux et al. (2008) as modified by Foster (2013), and wave fields (Schulz-Stellenfleth and Lehner 2004). SAR observed ubiquitous lines of enhanced wind stress curl aligned along the wind (Foster 2013) and made detailed descriptions of the storms' inner core.

An ITOP operations center at the Naval Postgraduate School in Monterey, California, coordinated the operations and issued customized forecasts for the program. A real-time data system presented analyses and model predictions of the atmosphere and ocean and displayed the locations and data from ITOP measurement systems. Atmospheric data and atmospheric model forecast products were archived and displayed by the National Center for Atmospheric Research Earth Observing Laboratory (NCAR/EOL; http://catalog.eol.ucar.edu/itop_2010/). Oceanic data, both in situ and remotely sensed, and ocean model forecast products were displayed primarily through a data system (https://

www.itop.org) at the Monterey Bay Aquarium Research Institute (MBARI). These systems used multiple sources for each of the critical decision quantities (storm track, storm intensity, ocean stratification, and expected ocean response) and displayed these in a uniform manner. The entire system was tested in the fall of 2009—one year before the actual program.

OVERVIEW OF THE ITOP STORMS. Tropical cyclone activity in the western Pacific was severely suppressed in 2010, with a weak monsoon trough over the Philippine Sea typical of La Niña conditions. Only 14 named storms occurred, compared to an average of 32. Three typhoons were observed extensively during the ITOP program (Table 1); each was spaced fortuitously so as to allow the evolution of storm wakes to be studied without the interference of subsequent storms.

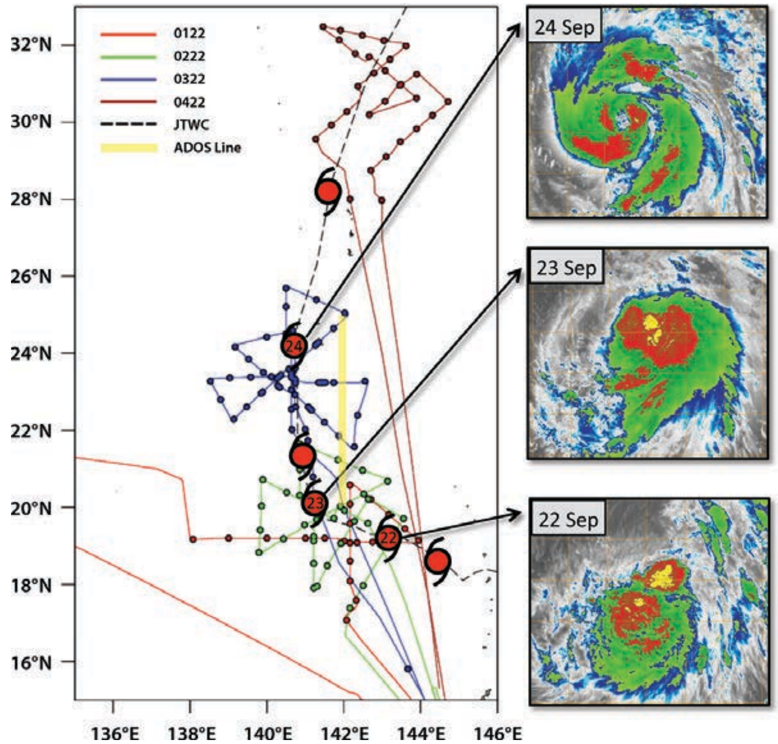


Fig. 4. As in Fig. 3, but for Typhoon Malakas.

Typhoon Fanapi (Fig. 3) grew from a tropical depression first defined on 1200 UTC 14 September. Three aircraft missions surveyed the storm environment to study its intensification and to provide additional data for the forecast models. Fanapi intensified in an environment of low vertical wind shear to a tropical storm on 0000 UTC 15 September and a typhoon on 1200 UTC 16 September. During this time, the track was complex, turning from northwest to northeast during the tropical storm to typhoon intensification and then back to west as a trough passed. On 17 September, while the storm was still tracking northeastward, a 350-km-long line of floats and drifters was deployed across the forecast storm track in anticipation of the westward turn. This flight, and two more, surveyed the storm as it passed through the middle of the array and reached maximum strength (105 kt; 1 kt = 0.51 m s^{-1}) on 18 September.

Additional flights deployed drifters into the storm wake. Meanwhile, on 16 September, the R/V *Revelle* was recalled to Taiwan; scientists arrived at the ship on 18–19 September just before Fanapi passed over Taiwan. The ship left Kaohsiung harbor on 20 September and reached the cold wake of the storm on 22 September, 4 days after the storm. The ship surveyed the wake until 9 October; gliders deployed from the ship continued to survey until about 21 October; drifters continued for much longer.

Typhoon Malakas (Fig. 4) developed as a tropical depression on 20 September as Typhoon Fanapi passed across the Taiwan Straits. The final Fanapi wake flight was diverted to make an initial survey of Malakas. The storm tracked northward during 22 and 23 September, but strong vertical wind shear from the north slowed intensification. As the wind shear relaxed on 24 September, maximum winds of 90 kt occurred and an extratropical transition began. These changes were documented in three flights on 23–25 September. Aircraft operations and oceanographic deployments were limited by the storm's passage close to Iwo-To and other Japanese islands. However, *RadarSat-2* imaged Typhoon Malakas on 22 and 24 September, yielding detailed maps of the wind and pressure fields (Fig. 5). On 29 September, after the storm had passed, six drifters were deployed into the wake along with an extensive AXBT wake survey.

Typhoon Megi (Fig. 6) grew from an area of organized convection, becoming a tropical depression as it passed south of Guam on 1800 UTC 12 October. Six WC-130J and one DOTSTAR flight measured its growth to tropical storm on 0600 UTC 13 October, to typhoon on 1200 UTC 14 September, and to one of the strongest supertyphoons ever recorded on 0240 UTC 17 October. Forecasts of Megi's turn from

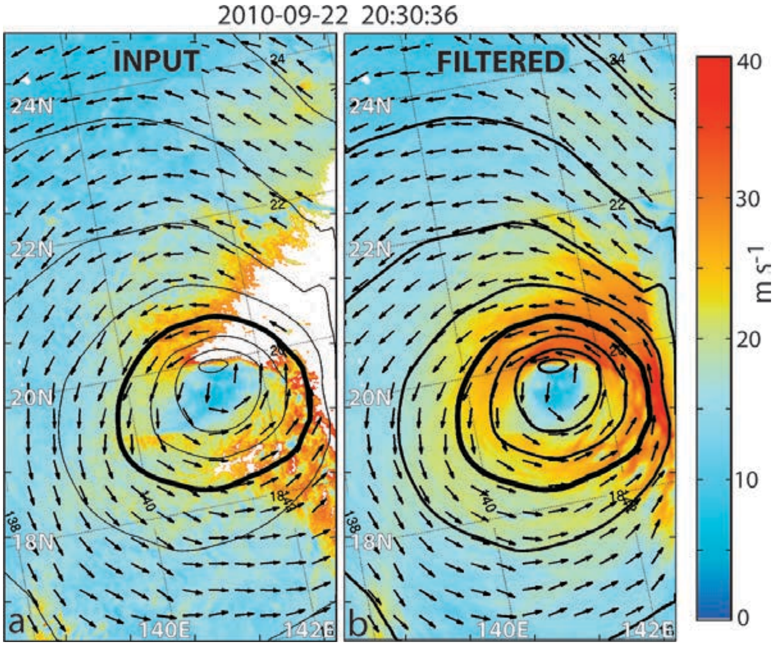
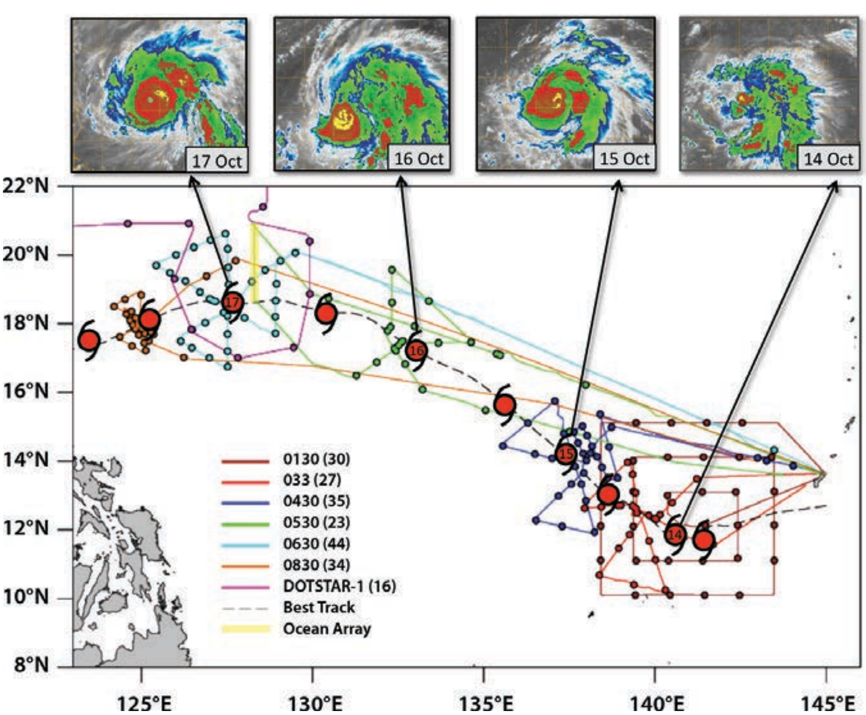


Fig. 5. Winds and pressure fields derived from *RadarSat-2* synthetic aperture radar (SAR) images for Typhoon Malakas on 22 Sep 2010. (a) SAR winds speed (colors) and direction (arrows) computed from SAR image (Horstmann et al. 2000, 2005; Wackerman et al. 1996; Foster 2013). Pressure fields (contours) are computed from winds and referenced to aircraft measurements (Patoux et al. 2008). (b) As in (a), but using a planetary boundary layer model to produce a scene-optimized wind field. Winds and pressures are calculated for 1-km pixels; wind directions are shown every 40 km.



F . 6. As in Fig. 3, but for Typhoon Megi.

northwestward to southwestward on 16–17 October contained large uncertainty. Nevertheless, a 200-km-long line of oceanographic floats was deployed perpendicular to the track on 16 October; the storm passed over the southern edge of that array later that day. The final ITOP flight measured Megi's cold wake in the region of peak intensity using air-deployed expendable current, temperature, and salinity (AXCP, AXBT, and AXCTD) probes. Megi then crossed the Philippines and re-emerged in the South China Sea, out of range for the survey aircraft, creating an unusually cold ocean wake (described in the section "Ocean Responses to the ITOP Storms"). A total of 10 synthetic aperture radar images of Typhoon Megi's core were collected from four different satellites (Fig. 7).

COMPARISON OF THE ITOP STORMS. The three storms occurred in diverse oceanic and atmospheric conditions. Supertyphoon Megi intensified over deep, warm mixed layers with high T100 values; Typhoon Malakas moved northward into a region of colder, shallower mixed layers and lower T100 values; and Typhoon Fanapi transited through the intermediate eddy-rich region. Fanapi and Megi formed from long-lived low-level circulations that moved westward in a nearly uniform easterly flow with intensification occurring steadily over a period of days under the influence of favorable ocean conditions and low to moderate vertical wind shear. Following formation, the two storms moved westward in similar atmospheric environments, but differing oceanic conditions. The pre-Malakas disturbance initially also moved westward in the broad easterly flow. However, the storm turned sharply poleward under the influence of a deep midlatitude trough and then moved northward through varying ocean conditions, resulting in a more complex combination of atmospheric and oceanic factors affecting its intensity.

Figure 8 compares the convective structures and size of these three storms by superimposing typical airborne radar eye images: the eyewall of Megi fits inside the eyewall of Fanapi, which in turn fits inside the eyewall of Malakas. With respective eye diameters of 17, 44, and 130 km for Megi, Fanapi, and Malakas, the entire storm structure of Megi including the eyewall and rainbands fits within the eye of Malakas. This illustrates the large range of storm structures that are typical of TCs in the western Pacific and the corresponding differences in the size of the cold wakes produced.

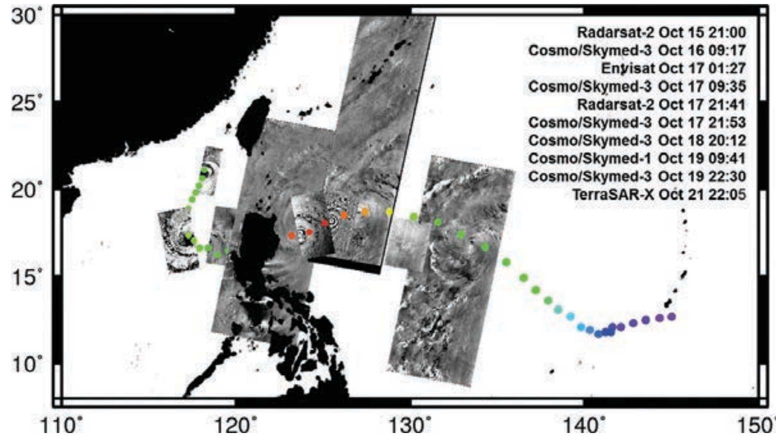


Fig. 7. Sequence of multisatellite radar data collections along the track of Typhoon Megi (dots).

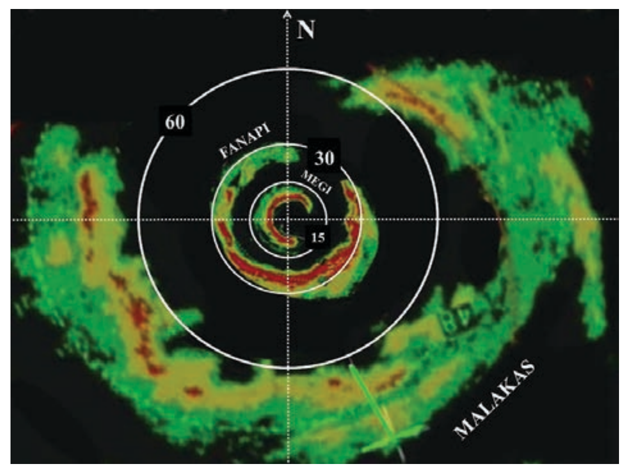


Fig. 8. Montage of airborne radar images of the eyewalls of typhoons Megi, Fanapi, and Malakas. Range rings are indicated by white circles with labels in km. The arrow indicates north.

The storm core structures also varied significantly (Table 1, Fig. 9). The core is characterized by the radius of maximum surface winds, the radius of flight-level (3 km) winds, the ratio of surface and flight-level maximum winds (Powell et al. 2009), and the slope defined by surface and flight-level wind maxima. These are computed from the difference in flight level (measured by WC-130J aircraft systems) and surface winds (measured by SFMR) near the time of maximum storm strength (Fig. 9, Table 1). For Typhoon Fanapi (Fig. 9a) the ratio of surface to flight level winds is 0.88 and the slope is 79 degrees. These values are similar to those of the typical hurricane over the North Atlantic (Powell et al. 2009; Hazelton and Hart 2013). Typhoon Malakas (Fig. 9b) has larger wind radii and a larger slope, but a smaller ratio of surface to flight-level winds. In contrast, Typhoon Megi (Fig. 9c) has smaller wind radii, a smaller slope, and a larger ratio of surface to flight-level winds.

OCEAN RESPONSES TO THE ITOP STORMS.

The cold wakes formed by the ITOP storms span a wide range of strengths and sizes (Fig. 10). Six wake events (Table 2)—the Fanapi, Malakas, and Megi wakes, a very different wake from Megi after it moved into the South China Sea (Megi-SC), a wake from Typhoon Lupit sampled by one of the moorings in 2009, and last the well-documented wake of Hurricane Frances (Sanford et al. 2011; D'Asaro et al. 2007)—are included in this analysis. Each storm's parameters are given for the time and location listed in Table 2 and marked by a star in each panel of Fig. 10.

Peak winds (U_{max}), from ITOP aircraft measurements if available or Cooperative Institute for Meteorological Satellite Studies (CIMSS) *SATCOM* estimates if not, span 41–70 m s^{-1}; the maximum stress likely spans a factor of about 2.5. The radius of maximum winds (R_{max}), from aircraft measurements if available or from CIMSS morphed imagery if not, span a factor of 4.5 (12–55 km) owing to the very small radius of Megi. Similarly, the storm translation speed (S) spans a factor of 3 (2.7–8 m s^{-1}), with Megi nearly stalling in the South China Sea and Malakas moving rapidly northward before undergoing extratropical transition. Ocean stratification, defined as the average temperature in the upper 100 m (T100), is estimated from temperature profiles measured by ITOP floats, drifters, moorings, or Argo floats. The wake strength (i.e., cooling), defined as the difference between prestorm SST to minimum wake temperature and estimated from a combination of ITOP measurements and microwave SST (Fig. 10), spans a factor of 4 (1.6°–7°C), with both extremes contributed by Megi. The wake width L_{wake} is estimated from the microwave images and defined as the width with 66% of the cooling; it varies by a factor of 10 (23–222 km). The offset of the wake from the track R_{wake} (see cartoon in Fig. 13f) ranges from zero for Megi-SC, because this wake is nearly centered on the track, to 78 km for Malakas.

These data can test simple models of TC wakes. We assume that air–sea fluxes are unimportant compared to vertical mixing of the underlying oceanic stratification (Price 2009), although the ITOP data are certainly rich enough to relax this assumption in a more detailed analysis. Storm strength is not correlated with colder wakes; the strongest storm, Megi in the Philippine Sea (Megi-PS), has the weakest wake (Fig. 13a). Price (2009) assumes, as a first rough approximation, that all storms mix to 100 m; the resulting wake temperature $T100_0$ depends only on the ocean temperature profile, and the wake cooling is $\Delta T100 = SST_0 - T100_0$. This is indeed only approximately true; the Megi-SC wake is colder than predicted and thus must be mixed to much deeper than 100 m, while the Malakas wake must be mixed significantly less deep (Fig. 13b). Price (1981) implicitly assumes that the width of the cold wake (L_{wake}) is set by the storm size; the ITOP data show this trend, with the smallest storm, Megi-PS, having the narrowest wake (Fig. 13e).

A key dynamical parameter is the nondimensional storm speed $S/2fR_{max}$, where f is the Coriolis frequency (Price 1981). For $S/2fR_{max} < 1$, a "slow" storm, storm winds persist at a single location for longer than $1/f$, so that an Ekman balance can be established; the cyclonic stress from the storm diverges the warm surface water away from the track, replacing it by cold upwelled water and creating a cold wake centered on the track. In the limit of $S/2fR_{max} = 0$, a stalled storm, upwelling continues indefinitely and the amount of cooling can be very large. In contrast, "fast" storms create a wake to the right of the storm track. Here the wind rotates clockwise with time and resonantly drives inertial currents in the mixed layer. The shear of these currents creates shear instability at the mixed layer base, leading to rapid mixed layer deepening. This is most effective for $S/2fR_{max} \sim 1$, when the maximum winds are approximately resonant. The radius of resonance moves farther rightward with

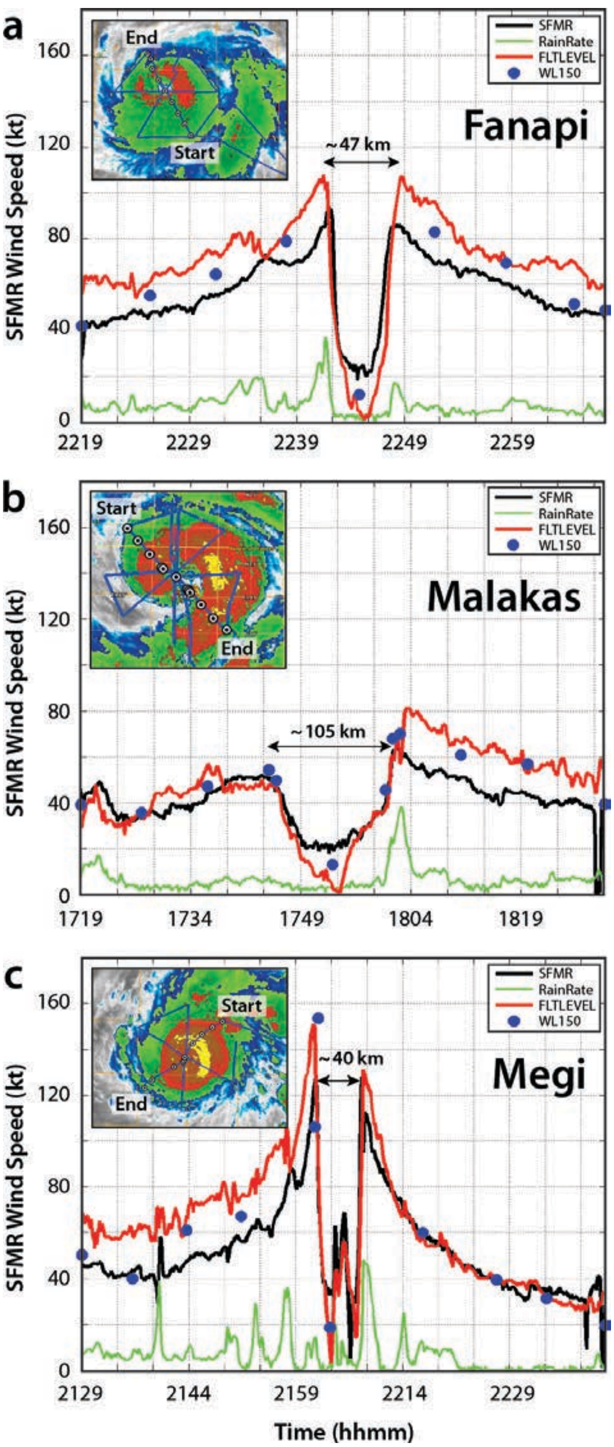


Fig. 9. Flight-level winds (kt, red line), surface winds (kt, black line), and surface rain rate (mm h^{-1}, green) for radial passes through (a) Typhoon Fanapi (flight 0620, pass 1), (b) Typhoon Malakas (0322 pass 2), and (c) Typhoon Megi (0630, pass 1). Solid blue dots are lowest 150-m dropsonde winds. The storm-relative flight track and dropsonde locations are shown on an MTSAT infrared image at the central time of the mission.

Table 2. Tropical cyclone wake properties.

	Date (2010), time, location	U_{max} (m s^{-1})	R_{max} (km)	Speed (m s^{-1})	Cooling (°C)	ΔT100 (°C)	R_{wake} (km)	L_{wake} (km)
Typhoon Lupit	20 Oct 2009, 1200–1800 UTC, 20.4°N, 127.5°E	44*	54	4.4	3.8	1.8	39	167
Typhoon Fanapi	18 Sep, 0000 UTC, 23.5°N, 126.3°E	50**	21	4.5	2.5	1.6	49	150
Typhoon Malakas	24 Sep, 0000 UTC, 24°N, 142°E	41**	55	8	3	5	78	222
Supertyphoon Megi-PS	16 Oct, 2000 UTC, 19°N, 128.4° E	70**	12	7	1.6	2	56	23
Supertyphoon Megi-SC	20 Oct, 1600 UTC, 19°N, 117°E	56*	55	2.7	7	2.7	0	222
Hurricane Frances	1 Sep 2004, 1800 UTC, 22°N 70°W	65*	40	6	2.1	1.4	75	111

* From CIMSS.

** From aircraft.

increasing storm speed, increasing the asymmetry of the wake, but also decreasing the magnitude of the currents, the mixing caused by them, and thus the amount of cooling. Figure 13d confirms the increasing rightward bias with increasing values of $S/2fR_{max}$. This can also be seen in Fig. 10: Megi-SC, the slowest storm, has a symmetrical wake whereas Megi-PS, Fanapi, and Malakas, all faster storms, have asymmetrical wakes. A remarkably strong dependence of wake cooling on $S/2fR_{max}$ (Fig. 13c) confirms the importance of this parameter. However, because the amount of cooling must also be influenced by the ocean stratification, the nearly perfect correlation in Fig. 13c must be at least partially due to the particular storms chosen and is not a general result.

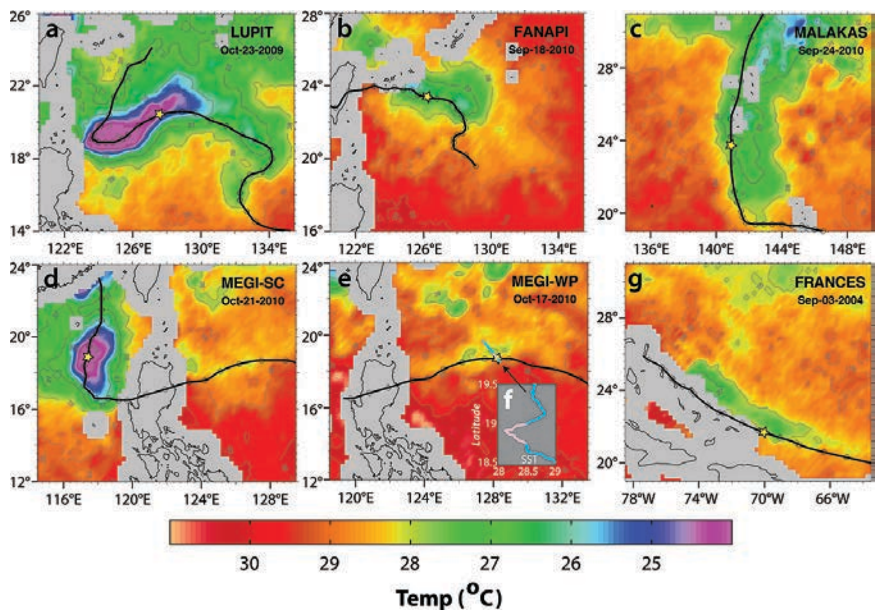


Fig. 10. (a)–(f) SST wakes of the ITOP storms. Color shows optimally mapped microwave SST (www.remss.com). Black line is the International Best Track Archive for Climate Stewardship (IBTrACS) storm track (Knapp et al. 2010) up to one day after the time of the map. Star shows region of wake analyzed here. Insert (f) shows SST across the very narrow wake of Megi as measured by the R/V *Revelle* on 17–20 Oct. (g) The wake of Atlantic Hurricane Frances. All panels use the same color map for temperature and are plotted on the same spatial scale.

Many features of the wakes are not captured by this simple analysis. The increasingly cold wake of Malakas to the north, despite its increasing speed, is probably due to the increasingly colder upper ocean temperatures. The lack of a cold wake in Megi-PS at its peak before encountering the Philippines, the cold circular feature in Fanapi's wake near its southern edge, and the very strong wake of Lupit near its northward turn (Fig. 10a) could easily be due to additional variability in the ocean and complexities in the storm track.

EVOLUTION OF STORM COLD WAKES.

ITOP measured the evolution of Typhoon Fanapi's cold wake for more than 3 weeks after the storm passage (Mrvaljevic et al. 2014). Figure 11 shows the evolution of upper ocean stratification at approximately the center of the wake. Mixing to about 100 m is apparent on day 261 (18 September 2010) as the storm passes over, creating an approximately 110-m-thick, 26°C mixed layer. This layer was capped by a warm layer within 3 days and thus becomes increasingly invisible in satellite SST measurements, most likely owing to the increased air–sea heat flux into the colder wake SST (Price et al. 2008). The cap created a subsurface layer that ITOP tracked for 37 days until it was mixed into the surface layer by the passage of Typhoon Chaba on 28 October. During this time, the surface layer thinned with an *e*-folding time of 23 days and was carried up to 300 km away from its generation site by the energetic eddies in this region.

The evolution of the Malakas cold wake has a similar pattern (Fig. 12). Mixing during the storm created an approximately 45-m-thick, 28°C mixed layer at the center of the wake (Fig. 12c). This layer was capped by a warm layer; the subsurface cold layer then thinned. After about 13 days the wake disappeared from Autonomous Drifting Ocean Stations (ADOS) observations (Fig. 12). During this time, the wake was distorted by the mesoscale eddy field. The southern edge of the wake moved northward; its western edge moved eastward, especially near 26°N (Figs. 12a,b). These displacements correspond to the oceanic velocity field (arrows) and the displacement of the drifter (white line). Similarly, a float deployed in Megi's western wake (e.g., Fig. 10e) observed a brief episode of capping within 12 h with a permanent cap forming 36 h after the storm passage (not shown here). A ship section across Megi's wake in

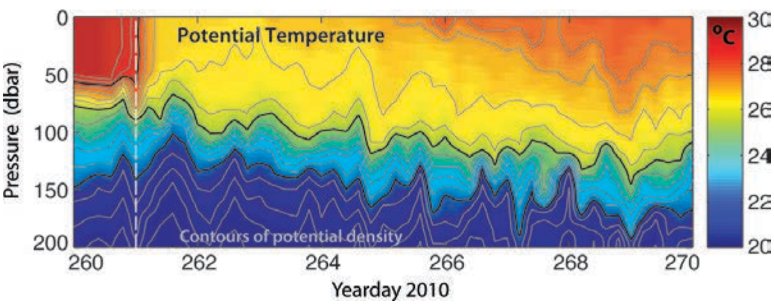


Fig. 11. Evolution of the Typhoon Fanapi wake. Potential temperature measured by a profiling EM-APEX float deployed near the center of the cold wake of Typhoon Fanapi. The storm creates a cold wake that is then capped by a thin, warm surface layer, but persists beneath this layer.

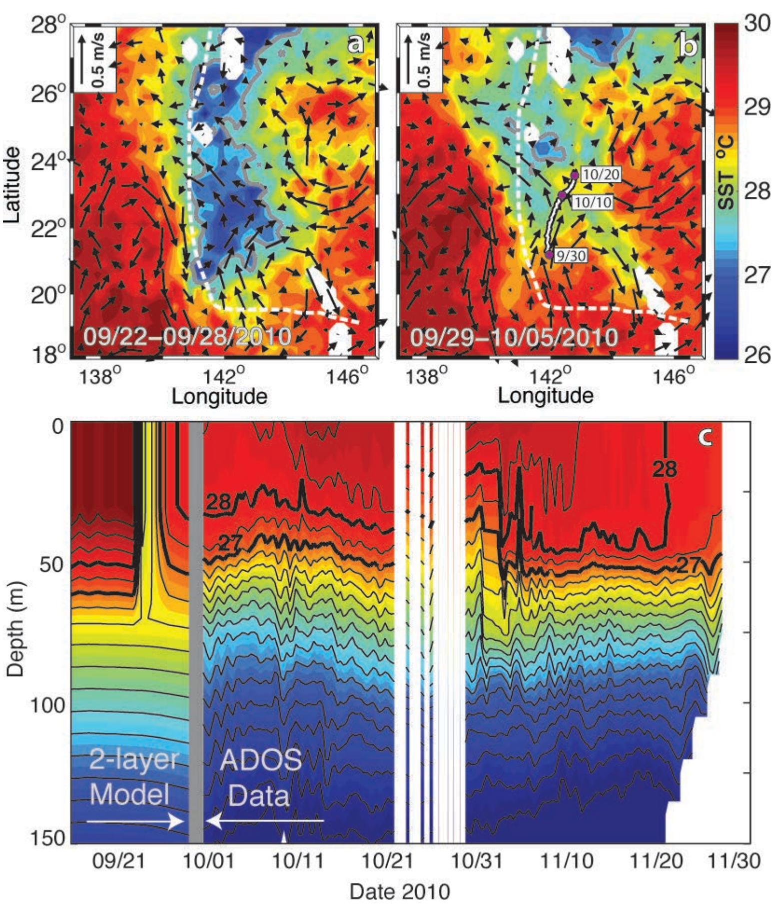


Fig. 12. Evolution of the Typhoon Malakas wake. (a),(b) Mean SST from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) (www.remss.com), with contoured 27.5°C isotherm (gray) and overlaid geostrophic velocity anomalies from Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO; Le Traon et al. 1998, black vectors) for the weeks of (a) 22 and (b) 29 Sep 2010, respectively. Track of ADOS drifter 82326 is superimposed (white); circles show position on 30 Sep and 10 and 20 Oct. White dashed line shows track of Typhoon Malakas. (c) Depth–time in situ temperature from drifter 82326 starting on about 30 Sep (colors and contours). Data before 30 Sep are computed using the two-layer model following Pun et al. (2007) based on satellite data and the Monthly Isopycnal and Mixed-Layer Ocean Climatology (Schmidtko et al. 2013) applied at the drifter deployment location.

the South China Sea (e.g., Fig. 10d) observed a capped wake 5 days after the storm passage. A mooring beneath Typhoon Lupit (e.g., Fig. 10a) observed a capped wake persisting for 10 days. In almost all cases, the actual wake lifetime may have been longer than observed because the wake could have moved away from the measurement platforms or persisted longer than the observations.

The ITOP data thus show that subsurface typhoon wakes, characterized by a subsurface minimum in stratification with the temperature of the storm's initial cold wake, are common. These features are 20–100 m thick with typical lifetimes of 10–30 days and they can be advected hundreds of kilometers from the storm track. Their decay is substantially faster than that expected from estimates of the ambient vertical diffusivity (10^{-4} m^2 s^{-1} over 20 days diffuses 13 m), suggesting that other mechanisms may be important in controlling their lifetime. For these late season storms, an ultimate lifetime of one month or so is set by the seasonal deepening of the mixed layer past the depth of the wake.

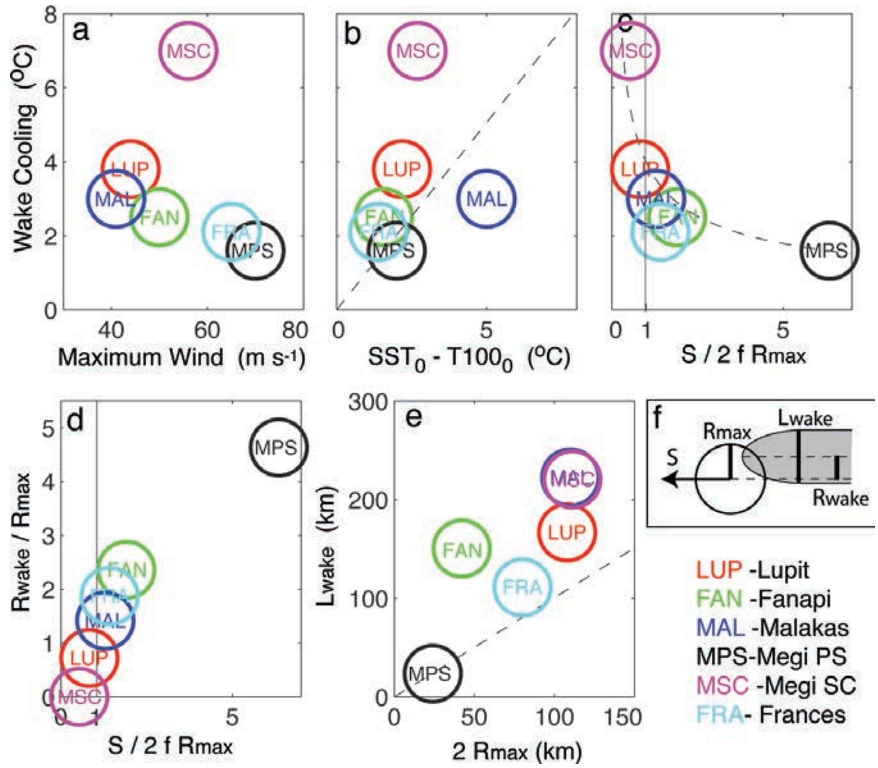


Fig. 13. Relationships between different properties of the six wakes in Fig. 10 and Table 2. (a) Wake cooling vs maximum wind. (b) Wake cooling vs ΔT100. (c) Wake cooling vs nondimensional storm speed. (d) Ratio of wake offset to R_{max} vs nondimensional storm speed. (e) Ratio of wake width to 2 R_{max}. (f) Graphical key to wake and storm properties. Dashed lines show 1:1 relationship in (b) and (e), and $4/(S/2fR_{max})^{1/2}$ in (c).

OCEAN CONTROLS ON AIR–SEA FLUXES.

ITOP was able to estimate directly the oceanic influence on air–sea fluxes by measuring ocean and atmospheric properties simultaneously using pairs of dropsondes and AXBTs deployed in each storm's inner core. Despite very similar warm (~29.5°C) precyclone SST (Figs. 2, 14a), the three ITOP typhoons developed in very different ocean environments, as shown by the profiles (Fig. 14a) and the corresponding differences in T100 (Fig. 1). Their contrasting development illustrates how differences in subsurface ocean thermal structure modify air–sea fluxes with potential impacts on typhoon intensity (Lin et al. 2013).

Typhoon Megi intensified over an unusually deep, thick subsurface warm layer (Fig. 14a) deepened from the already-deep baseline climatological values due to the 2010 La Niña. Because of this thick warm layer, Megi's fast translation speed, and its small size (Fig. 13d), SST beneath Megi cooled little (Fig. 14b). With SST remaining near 29°C and inner core air temperatures of ~27°C, air–sea temperature differences of ~2°C and corresponding humidity differences were maintained throughout Megi's intensification period. Enthalpy fluxes (Fig. 14c) increased with wind speed, thereby allowing the storm to intensify to its maximum potential (Emanuel 1988; Lin et al. 2013).

Typhoons Fanapi and Malakas intensified over regions with much shallower warm layers (Fig. 14a) and correspondingly lower T100 values (Fig. 1). This and their slower propagation speeds (Fig. 13c) resulted in SST cooling by 1°–2°C during intensification (Fig. 14b). For Fanapi, core air temperatures remained near 27°C, so the air–sea temperature differences decreased dramatically, reaching nearly zero at its peak wind of ~55 m s^{-1}. Humidity differences also decreased so that the total air–sea enthalpy flux (Fig. 14c) is less than half of Megi's flux at the same wind speed. The situation is similar, if less dramatic, for Malakas.

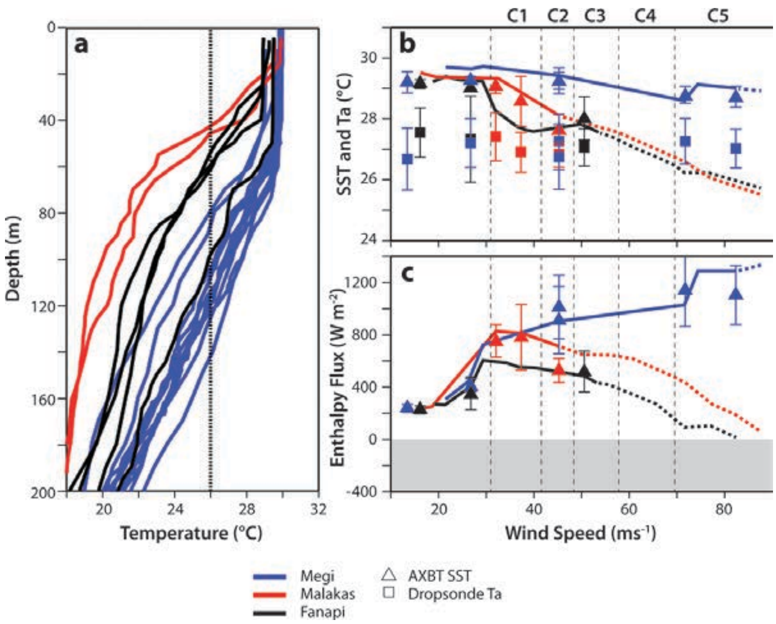


Fig. 14. Evolution of temperature and air–sea fluxes for three ITOP storms. (a) Prestorm temperature profiles for each ITOP storm from ARGO floats. (b) Symbols: SST and air temperature at the core of each storm as measured by dropsonde/AXBT pairs. Lines: results of an ocean model driven by the observed storms (solid) and extrapolated to higher wind speeds (dashed). (c) As in (b), but for estimated total enthalpy flux. Some of the AXBT profiles may be ~5 m shallow. Figure adapted from Lin et al. (2013).

Additional insight is obtained by simulating the additional reduction in core SST resulting from further storm intensification [Figs. 14b,c, dashed lines; see Lin et al. (2013) for details]. For Fanapi, SST decreases below the core air temperature, reversing the sign of the sensible heat flux and bringing the total flux to zero at a hypothetical wind speed of ~80 m s^{-1}. This reduction in core fluxes due to ocean cooling may play an important role in limiting the intensities of Fanapi and Malakas relative to Megi (Lin et al. 2013).

More detailed studies show other mechanisms by which ocean cooling influences TC structure. Dropsonde data collected in Typhoon Fanapi show the development of a stable boundary layer in the atmosphere over the colder SST in the right rear quadrant. This layer suppresses the transport of near-surface air into rainbands downstream of the cold SST, keeping air parcels near the warm ocean surface longer and increasing the inward turning of the wind over and downstream of the cold wake, a feature supported by results from high-resolution coupled atmosphere–ocean models (Chen et al. 2013; Lee and Chen 2014).

PERSPECTIVE. ITOP contained many more elements than can be addressed here. In particular, the experimental team worked closely with a modeling team, which included atmospheric, oceanic, and coupled variants. We have not addressed more detailed observations of ocean velocity or air–sea fluxes.

ITOP involved close cooperation between oceanographers and meteorologists and thus resulted in oceanic and atmospheric data fields measured on the same spatial scales. This allowed an analysis of the links between ocean dynamics, driven by storm fluxes, to SST and flux changes, and the resulting influences on the storm intensity. This cooperation was made possible by the rapid advances in technology available to measure the atmosphere and ocean under tropical cyclone conditions. Aircraft deployments of oceanographic and atmospheric probes and the ability to position long-lived ocean floats and drifters precisely into storms allows researchers to address the issues of air–sea interaction in these storms in fresh detail and examine the longer-term fate of the ocean perturbations introduced by the storms. Placement of these sensors greatly benefited from high-resolution models of both the ocean and atmosphere. Continued advances in understanding the interaction between the ocean and tropical cyclones will rely on continuing progress in the ability to make such observations, the ability to model these phenomena, and the clever use of these abilities by coordinated scientific teams.

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REFERENCES

Black, P. G., 1983: Ocean temperature changes induced by tropical cyclones. Ph.D. thesis, The Pennsylvania State University, 278 pp.

——, and Coauthors, 2007: Air–sea exchange in hurricanes: Synthesis of observations from the Coupled Boundary Layer Air–Sea Transfer experiment. *Bull. Amer. Meteor. Soc.,* **88,** 357–374, doi:10.1175/BAMS-88-3-357.

Centurioni, L. R., 2010: Observations of large-amplitude nonlinear internal waves from a drifting array: Instruments and methods. *J. Atmos. Oceanic Technol.,* **27,** 1711–1731, doi:10.1175/2010JTECHO774.1.

Chen, S. S., J. F. Price, W. Zhao, M. A. Donelan, and E. J. Walsh, 2007: The CBLAST-hurricane program and the next-generation fully coupled atmosphere–wave–ocean models for hurricane research and prediction. *Bull. Amer. Meteor. Soc.,* **88,** 311–317, doi:10.1175/BAMS-88-3-311.

——, W. Zhao, M. A. Donelan, and H. L. Tolman, 2013: Directional wind–wave coupling in fully coupled atmosphere–wave ocean models: Results from CBLAST-hurricane. *J. Atmos. Sci.,* **70,** 3198–3215, doi:10.1175/JAS-D-12-0157.1.

D'Asaro, E. A., and C. McNeil, 2007: Air–sea gas exchange at extreme wind speeds measured by autonomous oceanographic floats. *J. Mar. Syst.,* **66,** 92–109, doi:10.1016/j.jmarsys.2006.06.007.

——, T. B. Sanford, P. P. Niiler, and E. J. Terrill, 2007: Cold wake of Hurricane Frances. *Geophys. Res. Lett.,* **34,** L15609, doi:10.1029/2007GL030160.

Emanuel, K. A., 1988: The maximum intensity of hurricanes. *J. Atmos. Sci.,* **45,** 1143–1155, doi:10.1175/1520-0469(1988)0452.0.CO;2.

——, 1999: Thermodynamic control of hurricane intensity. *Nature,* **401,** 665–669, doi:10.1038/44326.

Eriksen, C. C., T. J. Osse, R. D. Light, T. Wen, T. W. Lehman, P. L. Sabin, and A. M. Chiodi, 2001: Seaglider: A long-range autonomous underwater vehicle for oceanographic research. *IEEE J. Oceanic Eng.,* **26,** 424–436, doi:10.1109/48.972073.

Foster, R. C., 2013: Signature of large aspect ratio roll vortices in synthetic aperture radar images of tropical cyclones. *Oceanography,* **26,** 58–67, doi:10.5670/oceanog.2013.31.

Graber, H. C., E. A. Terray, M. A. Donelan, W. M. Drennan, J. C. Van Leer, and D. B. Peters, 2000: ASIS—A new air–sea interaction spar buoy: Design and performance at sea. *J. Atmos. Oceanic Technol.,* **17,** 708–720, doi:10.1175/1520-0426(2000)0172.0.CO;2.

Hazelton, A. T., and R. E. Hart, 2013: Hurricane eyewall slope as determined from airborne radar reflectivity data: Composites and case studies. *Wea. Forecasting,* **28,** 368–386, doi:10.1175/WAF-D-12-00037.1.

Hong, X., S. W. Chang, S. Raman, L. K. Shay, and R. Hodur, 2000: The interaction between Hurricane Opal (1995) and a warm core ring in the Gulf of Mexico. *Mon. Wea. Rev.,* **128,** 1347–1365, doi:10.1175/1520-0493(2000)1282.0.CO;2.

Horstmann, J., W. Koch, S. Lehner, and R. Tonboe, 2000: Wind retrieval over the ocean using synthetic aperture radar with C-band HH polarization. *IEEE Trans. Geosci. Remote Sens.,* **38,** 2122–2131, doi:10.1109/36.868871.

——, D. R. Thompson, F. Monaldo, S. Iris, and H. C. Graber, 2005: Can synthetic aperture radars be used to estimate hurricane force winds? *Geophys. Res. Lett.,* **32,** L22801, doi:10.1029/2005GL023992.

——, C. Wackerman, S. Falchetti, and S. Maresca, 2013: Tropical cyclone winds retrieved from synthetic aperture radars. *Oceanography,* **26,** 46–57, doi:10.5670/oceanog.2013.30.

Jaimes, B., and L. K. Shay, 2009: Mixed layer cooling in mesoscale oceanic eddies during Hurricanes Katrina and Rita. *Mon. Wea. Rev.,* **137,** 4188–4207, doi:10.1175/2009MWR2849.1.

——, and ——, 2010: Near-inertial wave wake of Hurricanes Katrina and Rita over mesoscale oceanic eddies. *J. Phys. Oceanogr.,* **40,** 1320–1337, doi:10.1175/2010JPO4309.1.

Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone data. *Bull. Amer. Meteor. Soc.,* **91,** 363–376, doi:10.1175/2009BAMS2755.1.

Lee, C.-Y, and S. S. Chen, 2014: Stable boundary layer and its impact on tropical cyclone structure in a coupled atmosphere–ocean model. *Mon. Wea. Rev.,* **142,** 1927–1944, doi:10.1175/MWR-D-13-00122.1.

Leipper, D. F., 1967: Observed ocean conditions and Hurricane Hilda, 1964. *J. Atmos. Sci.,* **24,** 182–186, doi:10.1175/1520-0469(1967)0242.0.CO;2.

Le Traon, P. Y., F. Nadal, and N. Ducet, 1998: An improved mapping method of multisatellite altimeter data. *J. Atmos. Oceanic Technol.,* **15,** 522–534, doi:10.1175/1520-0426(1998)0152.0.CO;2.

Lévy, M., M. Lengaigne, L. Bopp, E. M. Vincent, G. Madec, C. Ethé, D. Kumar, and V. V. S. S. Sarma, 2012: Contribution of hurricanes to the air–sea CO_2 flux: A global view. *Global Biogeochem. Cycles,* **26,** GB2001, doi:10.1029/2011GB004145.

Lin, I.-I., C.-C. Wu, K. A. Emanuel, I. H. Lee, C.-R. Wu, and I.-F. Pun, 2005: The interaction of Supertyphoon Maemi (2003) with a warm ocean eddy. *Mon. Wea. Rev.,* **133,** 2635–2649, doi:10.1175/MWR3005.1.

——, ——, I. F. Pun, and D. S. Ko, 2008: Upper-ocean thermal structure and the western North Pacific category 5 typhoons. Part I: Ocean features and the category 5 typhoons' intensification. *Mon. Wea. Rev.,* **136,** 3288–3306, doi:10.1175/2008MWR2277.1.

——, and Coauthors, 2013: An ocean coupling potential intensity index for tropical cyclones. *Geophys. Res. Lett.,* **40,** 1878–1882, doi:10.1002/grl.50091.

Mrvaljevic, R. K., and Coauthors, 2014: Observations of the cold wake of Typhoon Fanapi (2010). *Geophys. Res. Lett.,* doi:10.1002/grl.50096, in press.

Niiler, P. P., 2001: The world ocean surface circulation. *Ocean Circulation and Climate,* G. Siedler et al., Eds., Academic Press, 193–204.

Patoux, J., R. C. Foster, and R. A. Brown, 2008: An evaluation of scatterometer-derived oceanic surface pressure fields. *J. Appl. Meteor. Climatol.,* **47,** 835–852, doi:10.1175/2007JAMC1683.1.

Powell, M. D., E. W. Uhlhorn, and J. D. Kepert, 2009: Estimating maximum surface winds from hurricane reconnaissance measurements. *Wea. Forecasting,* **24,** 868–883, doi:10.1175/2008WAF2007087.1.

Price, J. F., 1981: Upper ocean response to a hurricane. *J. Phys. Oceanogr.,* **11,** 153–175, doi:10.1175/1520-0485(1981)0112.0.CO;2.

——, 2009: Metrics of hurricane–ocean interaction: Vertically-integrated or vertically-averaged ocean temperature? *Ocean Sci.,* **5,** 351–368, doi:10.5194/os-5-351-2009.

——, J. Morzel, and P. P. Niller, 2008: Warming of SST in the cold wake of a moving hurricane. *J. Geophys. Res.,* **113,** C07010, doi:10.1029/2007JC004393.

Pudov, V., and S. Petrichenko, 2000: Trail of a typhoon in the salinity field of the ocean upper layer. *Atmos. Ocean Phys.,* **36,** 700–706.

Pun, I.-F., I.-I. Lin, C.-R. Wu, D.-S. Ko, and W. T. Liu, 2007: Validation and application of altimetry-derived upper ocean thermal structure in the western North Pacific Ocean for typhoon-intensity forecast. *IEEE Trans. Geosci. Remote Sens.,* **45,** 1616–1630, doi:10.1109/TGRS.2007.895950.

——, Y.-T. Chang, I.-I. Lin, T. Y. Tang, and R.-C. Lien, 2011: Typhoon–ocean interaction in the western North Pacific, Part 2. *Oceanography,* **24,** 32–41, doi:10.5670/oceanog.2011.92.

Romeiser, R., J. Horstmann, M. J. Caruso, and H. C. Graber, 2013: A descalloping post-processor for ScanSAR images of ocean scenes. *IEEE Trans. Geosci. Remote Sens.,* **51,** 3259–3272, doi:10.1109/TGRS.2012.2222648.

Sanford, T. B., J. F. Price, and J. B. Girton, 2011: Upper-ocean response to Hurricane Frances (2004) observed by profiling EM-APEX floats. *J. Phys. Oceanogr.,* **41,** 1041–1056, doi:10.1175/2010JPO4313.1.

Schmidtko, S., G. C. Johnson, and J. M. Lyman, 2013: MIMOC: A global monthly isopycnal upper-ocean climatology with mixed layers. *J. Geophys. Res.,* **118,** 1658–1672, doi:10.1002/jgrc.20122.

Schulz-Stellenfleth, J., and S. Lehner, 2004: Measurement of 2D sea surface elevation fields using complex synthetic aperture radar data. *IEEE Trans. Geosci. Remote Sens.,* **42,** 1149–1160, doi:10.1109/TGRS.20O4.826811.

Shay, L. K., 2010: Air–sea interactions in tropical cyclones. *Global Perspectives on Tropical Cyclones: From Science to Mitigation,* J. C. L. Chan and J. D. Kepert, Eds., World Scientific, 93–131.

Uhlhorn, E. W., P. G. Black, J. L. Franklin, M. Goodberlet, J. Carswell, and A. S. Goldstein, 2007: Hurricane surface wind measurements from an operational stepped frequency microwave radiometer. *Mon. Wea. Rev.,* **135,** 3070–3085, doi:10.1175/MWR3454.1.

Wackerman, C. C., C. L. Rufenach, R. A. Shuchman, J. A. Johannessen, and K. L. Davidson, 1996: Wind vector retrieval using ERS-1 synthetic aperture radar imagery. *IEEE Trans. Geosci. Remote Sens.,* **34,** 1343–1352, doi:10.1109/36.544558.

Wright, C. W., and Coauthors, 2001: Hurricane directional wave spectrum spatial variation in the open ocean. *J. Phys. Oceanogr.,* **31,** 2472–2488, doi:10.1175/1520-0485(2001)0312.0.CO;2.

Wu, C.-C., and Coauthors, 2005: Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR): An overview. *Bull. Amer. Meteor. Soc.,* **86,** 787–790, doi:10.1175/BAMS-86-6-787.

Yablonsky, R. M., and I. Ginis, 2013: Impact of a warm ocean eddy's circulation on hurricane-induced sea surface cooling with implications for hurricane intensity. *Mon. Wea. Rev.,* **141,** 997–1021, doi:10.1175/MWR-D-12-00248.1.

ERA-CLIM

Historical Surface and Upper-Air Data for Future Reanalyses

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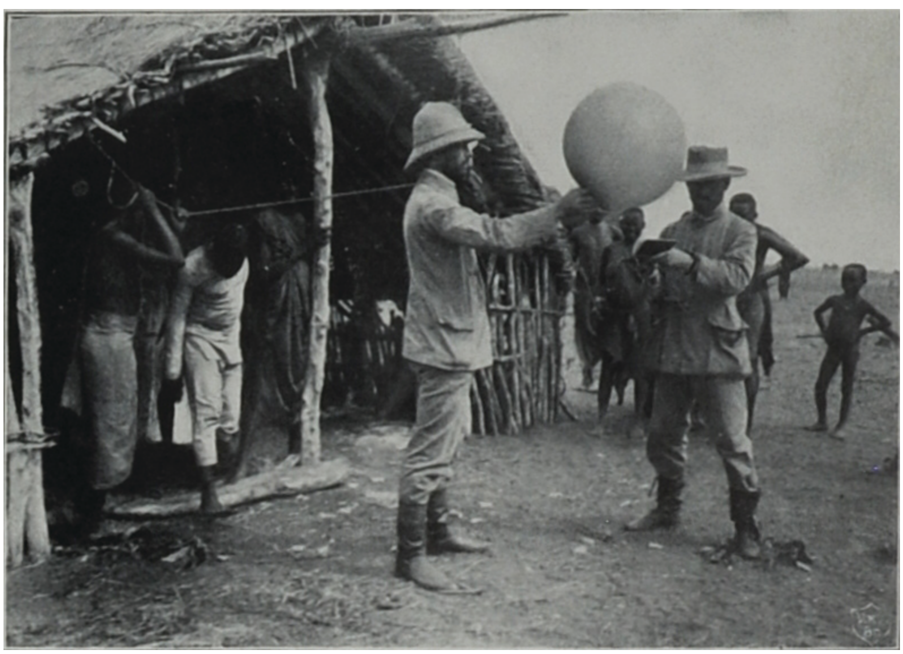
Newly digitized surface and upper-air data are useful to analyze climate and weather events in the first half of the twentieth century and may help to improve future reanalyses.



Pilot balloon ascent at the Mori Bay (Victoria Nyanza) during the German East Africa Expedition 1908 (from Berson 1910).

Currently, several widely used reanalyses are available reaching back to at least 1958, giving physically consistent, detailed pictures of the atmospheric state in space and time: The 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005), the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) 50-yr Reanalysis (NNR; Kistler et al. 2001), the newly completed Japanese 55-year Reanalysis Project (JRA-55; Ebita et al. 2011), and the Twentieth Century Reanalysis (20CR; Compo et al. 2011). Climate Forecast System Reanalysis Lite (CFSR-lite; Saha et al. 2010) is planned to replace NNR in the near future. JRA-55, ERA-40, and NNR cover the well-observed period back to ▶

the IGY in 1957/58 and to 1948. They have used surface as well as upper-air and satellite observations. However, the relatively short period of data does not cover several prominent climate or weather events in the first half of the twentieth century. 20CR, on the other hand, has assimilated synoptic surface and sea level pressure only, using monthly sea surface temperatures and sea ice information as boundary conditions. This has allowed for an extension of the period covered by reanalyses back to 1871. However, to date, no reanalysis has made use of the significant amount of historical upper-air data before 1948, even though this type of product is expected to profit from assimilating further historical surface as well as upper-air data.

In the framework of the European Reanalysis of Global Climate Observations (ERA-CLIM; www.era-clim.eu) project, a European Union (EU) Seventh Framework Programme for Research and Technological Development (FP7) project designed to prepare input data and assimilation systems for a new global atmospheric reanalysis of the twentieth century, significant amounts of pre-1957 upper-air and surface data have been cataloged (>1.25 million station days each), imaged (>450,000 images), and digitized (>700,000 station days each), with the aim to prepare new input datasets for upcoming reanalyses. The data rescue activities constituted one important work package of the project, besides the preparation of satellite, boundary condition, and forcing data; the integration of the observational data into the ECMWF Observation Feedback Archive (OFA); and the quantification and reduction of errors and uncertainties in the observational data. The inventoried and digitized data cover large parts of the globe, focusing on so far less well-covered regions such as the tropics, the polar regions, and the oceans and on very early twentieth-century upper-air data from Europe and the United States. The total number of digitized/inventoried records produced in ERA-CLIM, in the form of time series of meteorological data at fixed stations or from moving observational platforms, is 80/214 for surface stations, 735/1,783 for upper-air stations, and 61/101 for moving upper-air platforms (i.e., data from ships, etc.).

A rough estimate of the relative contribution of ERA-CLIM to the total historical upper-air data record available in digital form can be obtained from Fig. 1, which will be discussed in more detail in the section on data distribution over time. In this figure, the number of Integrated Global Radiosonde Archive (IGRA) radiosonde records (Durre et al. 2006) after 1957 corresponds by and large to the number of upper-air records assimilated into ERA-40 (see Fig. 1 of Ramella-Pralungo et al. 2014). Summing up the area between the curves and using a constant number of 877 records in IGRA from 1971 onward gives an additional contribution of ERA-CLIM to the number of assimilated upper-air records × months in ERA-40 (~415,000) of 15.9%. Taking both ERA-40 and the Comprehensive Historical Upper-Air Network (CHUAN; Stickler et al. 2010), which already compiled large amounts of historical (i.e., pre-1957) upper-air data, together, the additional contribution of ERA-CLIM is still considerable (8.6%). Note that, on one hand, these numbers tend to overestimate the volume of historical data, because the earlier series have generally fewer observations per day and reach lower altitudes above sea level than the more recent ones. On the other hand, the historical observations are especially valuable farther back in time, as the total number of assimilated observations in the reanalyses decreases.

A very important aspect of the project itself was the international collaboration reaching beyond the so-called European research area (http://ec.europa.eu/research/era/index_en.htm), which comprises a system of scientific research programs integrating the scientific resources of the European Union since the year 2000. Besides several institutions from countries within the European Research Area—namely, the University of Bern (UBERN; Switzerland) and the Fundação da Faculdade de Ciências da Universidade de Lisboa, together with the Dom Luiz Institute of the University of Lisbon (FFCUL; Portugal)

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and Météo-France (METFR) in Toulouse, France—two institutions from outside the European Research Area contributed to the data rescue activities of ERA-CLIM: the Russian Research Institute for Hydrometeorological Information (RIHMI) in Obninsk, Russia, and the Universidad del Pacífico (UPAC) in Santiago, Chile. As a result, ERA-CLIM had access to archives that were previously inaccessible to the international scientific community. Furthermore, the collaboration allowed for an intense exchange and knowledge transfer between the partner institutions with respect to data rescue techniques such as imaging, job handling (for which a web interface was developed), and experiences with optical character recognition software and quality check (QC) tests. Finally, a large, albeit still incomplete, catalog of available historical data sources was developed and made available in the form of a web-based metadatabase, which can serve as a starting point for further data rescue projects.

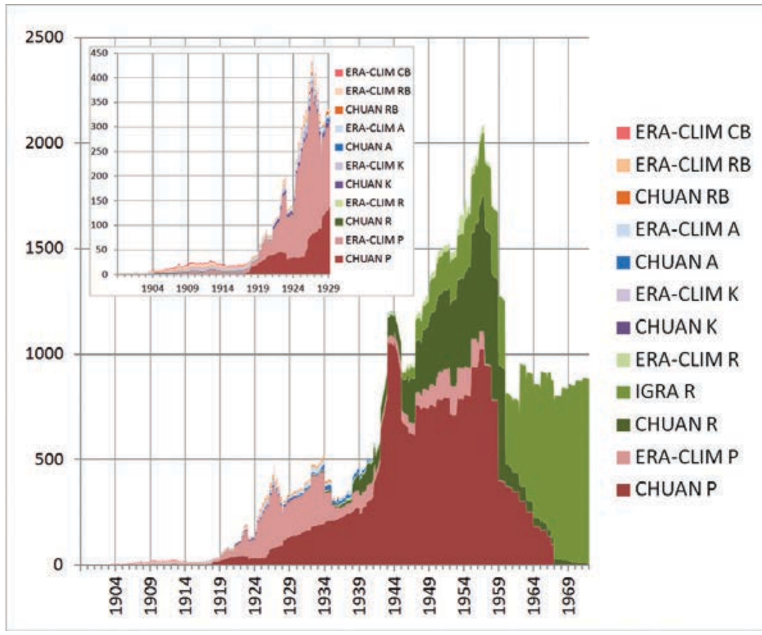

Fig. 1. Number of inventoried ERA-CLIM upper-air records, available CHUAN upper-air records (without merged IGRA records), and IGRA radiosonde records vs time (1900–72; Durre et al. 2006). Records that have multiple measurement platforms (19 of 1,783) are counted multiply. The abbreviations in the figure are as follows: CB is captive balloon, RB is registering balloon, A is aircraft, K is kite, R is radiosonde, and P is pilot balloon.

The data rescue activities of ERA-CLIM were organized in close arrangement with the broader Atmospheric Circulation Reconstructions over the Earth initiative (ACRE; www.met-acre.org; Allan et al. 2011) and, in the case of surface pressure and temperature data, in cooperation with the International Surface Pressure Databank (ISPD; http://reanalyses.org/observations/international-surface-pressure-databank; Compo et al. 2011) and the International Surface Temperature Initiative (www.surfacetemperatures.org; Thorne et al. 2011). The new ERA-CLIM data will be made available online (via www.era-clim.eu). The upper-air data (Stickler et al. 2014) will be included in the CHUAN collection and are also available online (at http://doi.pangaea.de/10.1594/PANGAEA.821222). The full station record documentation including station name, location/elevation, time coverage, measurement platform, estimated number of station days, and data source are provided online in the metadatabase (see www.oeschger-data.unibe.ch/metads). More detailed information on the cataloging and digitization of the surface and upper-air data, on the quality checks applied, and on the largest upper-air sources can be found in Morozova and Valente (2012) and Stickler et al. (2014).

THE ERA-CLIM SURFACE AND UPPER-AIR DATA.

Data sources. Potential data sources were identified in different ways. A first part of the sources was inventoried inside the archives of the institutions involved in the project (first institution in each group of the following) or in other national archives that these had access (other institutions listed): FFCUL and Portuguese national weather service Instituto Português do Mar e da Atmosfera; RIHMI; METFR and French National Archives in Fontainebleau; UPAC, Dirección Meteorológica de Chile, Naval and Maritime Museum in Valparaíso, and Chilean Navy; and Met Office (UKMO) and National Meteorological Library and Archives. These sources were often weekly, monthly, or yearly reports or original observation diaries of national meteorological services. A second part of the sources, all upper-air, was identified in a large web-based literature research conducted at UBERN. For example, further meteorological reports could be obtained from or imaged directly at libraries, but also many published reports from historical measurement campaigns and expeditions and from observatories were collected.[1] The last part consists of sources that were already available in the form of digital images from the National Oceanic and Atmospheric Administration (NOAA) Central Library Foreign Climate Date website (http://docs.lib.noaa.gov/rescue/data_rescue_home.html).

More data sources were identified, cataloged, and imaged than could be digitized within the budget and time restrictions determined by the project plan. These additional sources, broken down to the single records, are also contained in the complete project station inventory (www.oeschger-data.unibe.ch/metads) to prevent duplicate efforts within the international data rescue community. Furthermore, they will be of great use for the continued data rescue efforts in the framework of the follow-up project ERA-CLIM2, begun in January 2014.

Imaging, digitization, quality checks, and reformatting. All identified sources were imaged with digital cameras at the different institutions in high resolution and have been centrally stored at UBERN. Digitization was done either by manual keying or, whenever possible, with optical character recognition (OCR) software. The latter method could be used extensively at FFCUL and RIHMI, where large sources were in very regular, tabular formats, but only for a small part of the very diverse sources at UBERN.

The QC consisted of flagging of suspicious values during the digitization process, checking these values afterward with the help of the digital images, and range checks. The qualification of values as suspicious was generally based on expertise, considering, for example, implausible or doubtful values such as 370° for wind direction or 200 m s^{-1} for wind speed, strong outliers in vertical profiles of temperature and wind speed, deviations from monotonously increasing values of geopotential height with altitude, etc. Additional tests were performed with the surface data at FFCUL (e.g., consistency with monthly checksums) and with the upper-air data digitized at RIHMI (e.g., vertical consistency checks using the hydrostatic equation). Finally, departures from the new ERA-CLIM surface-only reanalysis (ERA-20C; Poli et al. 2013) were used for QC in case of the complete upper-air temperature values. The QC applied to the complete upper-air data is described in much more detail in Stickler et al. (2014). All digitized and quality checked records have been reformatted to ASCII files.

[1] For example, German East Africa expedition of 1908 (Berson 1910; Süring 2013; Brönnimann and Stickler 2013); the Swiss Greenland expedition of 1912/13 (de Quervain et al. 1920); the Norwegian North Polar expedition with the Maud in 1918–25 (Sverdrup 1933a,b); the German Atlantic expedition with the Research Vessel *Meteor* in 1925–27 (Kuhlbrodt and Reger 1933); the Greenland expedition of the University of Michigan of 1926–31 (Hobbs and Fergusson 1931); the German Greenland expedition of 1930/31 (Holzapfel et al. 1939); the Byrd Antarctic expeditions of 1928–30 and 1930–35 (Grimminger and Haines 1939); and the Canadian polar year expeditions of 1932/33 (Meteorological Services of Canada 1940; see also various reports of the Harvard, Lindenberg, Blue Hill, Mt. Weather, Samoa, Batavia, and Helwan astronomical/meteorological/magnetic observatories).

Table 1. Estimated number of digitized/inventoried station days for different measurement platforms and time periods.

Measurement platform	Pre-1928 digitized, inventoried		1928–37 digitized, inventoried		1938–47 digitized, inventoried		1948–57 digitized, inventoried	
Surface	568,573	1,041,209	118,512	248,172	19,446	108,313	0	30,987
Aircraft	9,116	12,759	14,077	25,756	1,421	3,322	0	0
Captive balloon	6,423	7,076	485	652	0	0	0	0
Kite	24,506	29,208	978	3,820	0	0	0	0
Pilot balloon	64,198	188,826	175,044	416,538	156,273	221,958	172,229	334,567
Radiosonde	0	0	1,368	1,614	13,336	21,168	79,710	164,047
Registering balloon	13,368	18,201	3,580	6,685	0	0	0	0
Various moving upper air	2,717	2,866	2,256	5,763	0	0	328	328
Atmospheric transmission	2,694	2,694	496	536	0	0	379	409

Distribution of the data in space and time. As can be seen from Table 1, the largest fraction of the inventoried and digitized data with respect to station days consists of regular surface station and pilot balloon wind observations. After 1938, radiosonde observations also contribute significantly to the total amount of data. The largest fraction of the surface data is from the period before 1928. Aircraft, kite, and registering[2] or tethered[3] balloon observations are almost exclusively from the period before 1938. The quantity of the moving platform upper-air data (i.e., data from ships, aircraft, etc.) is much smaller than that of the regular, station-based upper-air observations. Nevertheless, these data might turn out to be important to improve the quality of future reanalyses, as they often come from oceanic regions that are not covered by any other data source in the historic time. Finally, a few additional, early atmospheric transmission records have been digitized in the framework of ERA-CLIM. Complete lists of all parameters contained in the surface, upper-air, and atmospheric transmission station observations are given in Tables 2–4.

Figure 2 shows the global distribution of the surface stations that have been inventoried. They are partly located in mainland Portugal, on the Portuguese islands of Madeira and the Azores, and in former Portuguese colonies in Africa and Asia. The rest of the stations are located in Chile, covering the full latitudinal transect from 20° to 55°S east of the Pacific Ocean, including Easter Island and the Robinson Crusoe Island in the southeastern Pa-

Table 2. Observed parameters contained in the surface station data files.

Parameter	Unit
Wind speed	m s^{-1}
Wind direction	°
u wind	m s^{-1}
v wind	m s^{-1}
Surface pressure	hPa
Sea level pressure	hPa
Pressure temperature	°C
Temperature	°C
Maximum temperature	°C
Minimum temperature	°C
Grass maximum temperature	°C
Grass minimum temperature	°C
Soil temperature	°C
SST	°C
Relative humidity	%
Water vapor pressure	mm
Absolute humidity	g m^{-3}
Dewpoint temperature	°C
Wet-bulb temperature	°C
Cloud cover	oktas
Sunshine duration	h
Precipitation	l m^{-2}
Precipitation duration	hhmm
Evaporation	l m^{-2}
Actinometric values	°C
Irradiation max temperature	°C
Irradiation min temperature	°C
Sunshine duration percentage	%
Visibility	m
Present weather	
Past weather	

[2] Registering balloons are weather balloons carrying registering instruments without being equipped with a radio transmitter.

[3] Tethered balloons are weather balloons kept connected to a line to the ground (tether) during ascent and carrying registering instruments.

Table 3. Observed parameters contained in the upper-air station data files. Pressure is only contained in the files based on altitude levels MSL; geopotential height is only in files based on pressure levels.

Parameter	Unit
Pressure/geopotential height	hPa/gpm
Temperature	°C
Wind direction	°
Wind speed	m s^{-1}
u wind	m s^{-1}
v wind	m s^{-1}
Relative humidity	%
Dewpoint difference	K
Specific humidity	g kg^{-1}

Table 4. Observed parameters contained in the atmospheric transmission station data files.

Parameter	Unit
Lambda	μm
Transmissivity	%/100

cific and around the South China Sea region (South China, East China, and Philippine Seas, and Sea of Japan). Many of these records start in the nineteenth century: at present, data coverage is for the August 1873–January 1879 and 1894–1941 periods, with efforts now underway to fill the gap in these records for both new versions of 20CR and ERA-CLIM2 (R. Allan 2013, personal communication).

Figure 3 presents the locations of all inventoried upper-air stations, separately for the different observation platforms. The CHUAN stations [most comprehensive historical (i.e., pre-1957), upper-air dataset] that were already available before the ERA-CLIM project and IGRA stations (most comprehensive radiosonde dataset after 1957) are shown for comparison. The vast majority of all stations and also of the stations shown in the top-left panel of Fig. 3 are pilot balloon stations, followed by radiosonde stations.

A large number of pilot balloon, registering balloon, and captive balloon stations are located in Europe, India, and Pakistan. Many more such stations can be seen in North and South America, Greenland, Africa, and parts of Asia. Particularly, in parts of South America (e.g., Bolivia), Africa (e.g., Egypt, southeastern Africa), Russia, and Europe (e.g., United Kingdom, France, Spain), the stations are located in areas not at all covered by CHUAN. For other regions, especially Europe and the United States but also India, ERA-CLIM stations are often already available in CHUAN but not for the early periods covered by the ERA-CLIM records (cf. Fig. 4, top).

The ERA-CLIM radiosonde stations are mainly located in the former Soviet Union, France including French overseas territories, the former Portuguese colonies, and some other African countries. For most of them, CHUAN already contains data but again largely for a later time. The additional IGRA stations show the difference to the maximum extent of the post-1957 global radiosonde network. For these stations, there exists presumably no or very little pre-1958 data.

There are many more aircraft stations in the ERA-CLIM data that were not contained in CHUAN

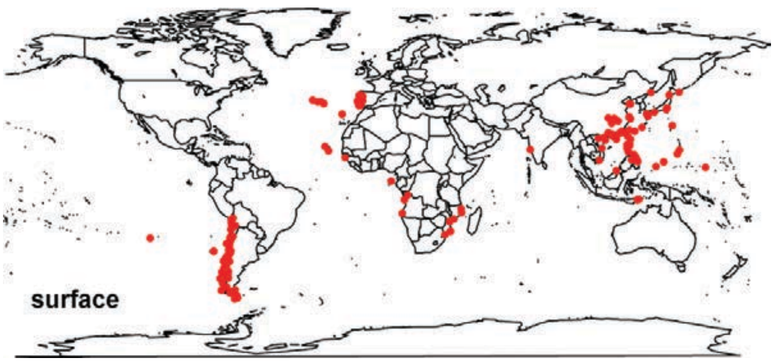

Fig. 2. Map showing the global distribution of all inventoried ERA-CLIM surface stations.

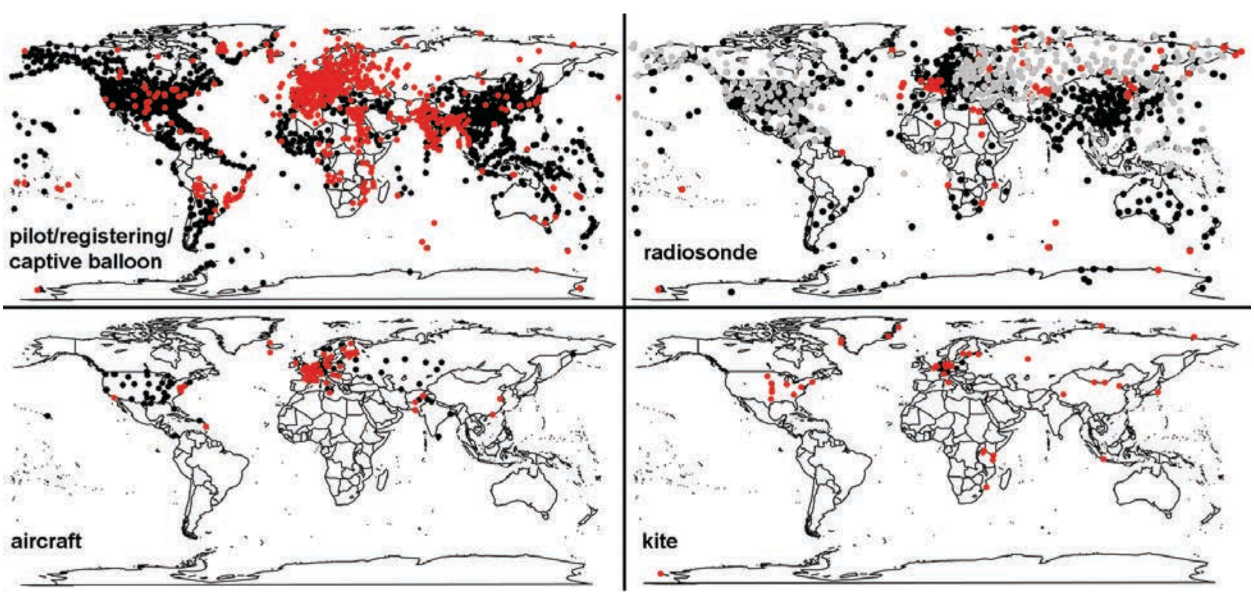

Fig. 3. Maps showing the global distribution of all inventoried ERA-CLIM upper-air stations (red) and additional available CHUAN upper-air stations (black). Measurement platforms are presented separately. (top right) Radiosonde displays all pre-1958 IGRA stations (gray), together with the additional CHUAN and ERA-CLIM stations.

(e.g., in France, Iceland, Finland, Pakistan, and China). Finally, many additional early kite observations from Europe but also from the United States (for which they are only available as monthly-mean values in CHUAN) have been digitized, and kite stations additional to the ones in CHUAN can be seen for Greenland, Russia, China, Indonesia, and southeastern Africa.

Figure 4 displays the changing upper-air station network in the ERA-CLIM as well as CHUAN datasets with time for the period before 1958. It is clear from both top panels that ERA-CLIM contributes a lot of new stations compared to CHUAN, particularly in the very early periods before the 1940s. For the later periods, there are also many new records, but with a focus on the tropics, the former Soviet Union, and France including overseas territories. Many further records during these periods are filling time gaps that were present in CHUAN. Some records (former Portuguese colonies) continue into the 1970s.

Going back to Fig. 1 in more detail, this graph shows the monthly resolved number of inventoried ERA-CLIM and CHUAN records from 1900 to 1972, when the last upper-air record digitized in ERA-CLIM ends, subdivided into observation platforms. This representation demonstrates during which periods the new ERA-CLIM observations significantly increase the already available amount of data and that the data rescue efforts in the framework of ERA-CLIM focused on the pre-1958 period. Large amounts of additional pilot balloon records have been inventoried (and partly digitized) for 1920–35, with the new ERA-CLIM data contributing mostly more than 50% to the available total amount until 1934. The ERA-CLIM pilot balloon records also significantly contribute to the total amount of data during the years 1935–40 and after 1946. The largest contribution of ERA-CLIM to the total radiosonde records occurs during the period 1947–56 and during the early radiosonde era before 1938 (albeit on a very low absolute level in the latter case). The number of kite records is not only strongly increased relative to CHUAN before 1928, but ERA-CLIM also provides the early U.S. kite data as single ascents that were only available as monthly means until now, as mentioned above. With respect to aircraft data (without airship observations that are contained in the moving upper-air inventory), the ERA-CLIM dataset has a large relative contribution (often >50%) from 1918 to 1937, with the largest absolute contribution in the 1930s. Also for the registering balloons, the new ERA-CLIM data offer more records than CHUAN most of the time.

The right panels of Figs. 4 and 5 of Stickler et al. (2010) give a good indication of the typical vertical distribution of historical upper-air data over time in the first half of the twentieth century (as can be seen from Fig. 1, the records in these figures, derived for CHUAN but similar to the ERA-CLIM data, are dominated by visually tracked pilot balloons, except for the period before 1918, with radiosondes contributing up to one-third to the total number of records after the mid-1940s): Until the late 1930s, most daytime

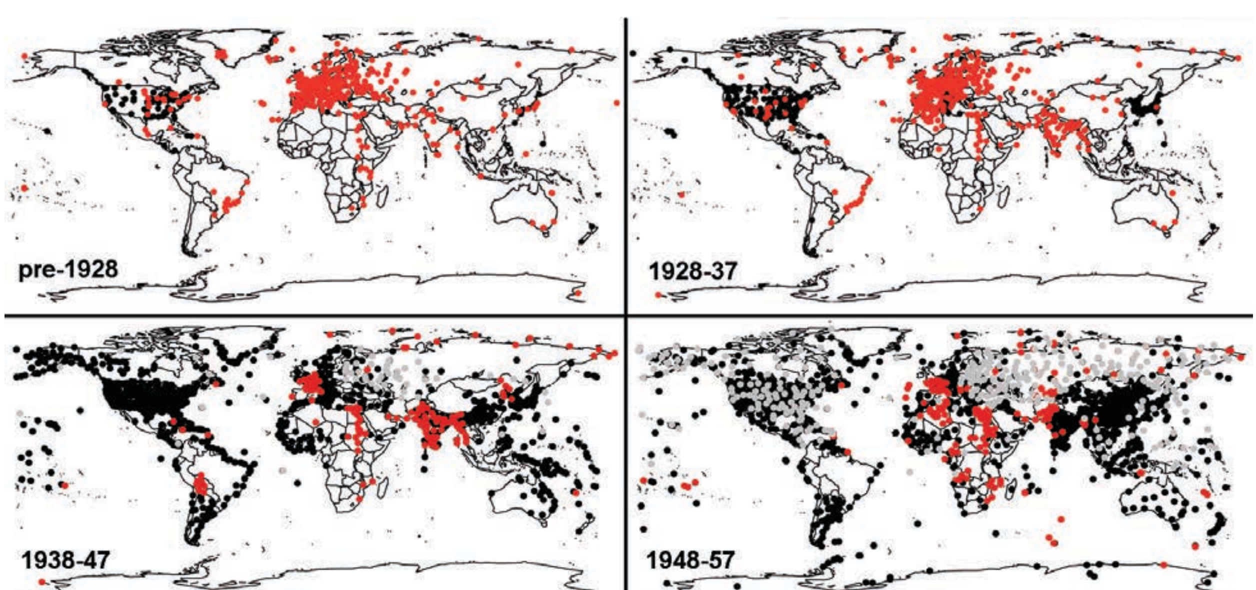

Fig. 4. Maps showing the global distribution of all IGRA radiosonde stations, additional inventoried ERA-CLIM upper-air stations (red), and available CHUAN upper-air stations (black) for the pre-1928 period and for the decades 1928–37, 1938–47, and 1948–57.

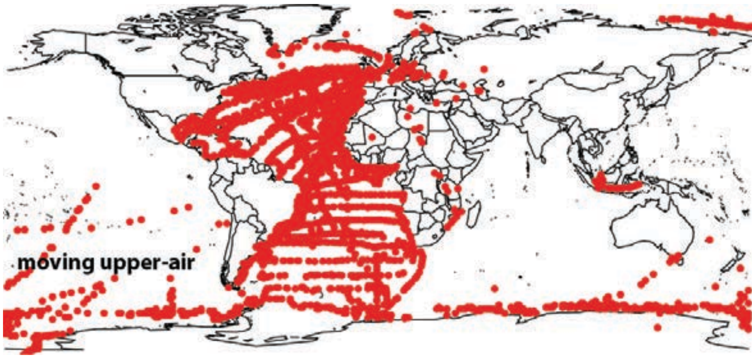

Fig. 5. Map showing the global distribution of the locations of all inventoried ERA-CLIM moving upper-air data.

(0600–1800 UTC) ascents did not reach altitudes higher than 5,000 m above mean sea level (MSL). In the middle to late 1940s, already 15%–25% of these ascents reached altitudes of at least 8,000 m MSL. During the same period, the contribution of ascents with top heights of more than 13 km MSL became significant. From about 1950 on, more than 15% of the daytime sondes reached altitudes above 20 km MSL; after 1955, a small part has top levels above 30 km MSL. For nighttime ascents and climatic regions with high frequencies of cloud cover, the values tend to be lower in case of the visually tracked balloons.

Another estimate of typical heights reached during historical upper-air observations of different types can be obtained from ascents performed during the German Atlantic expedition of 1925–27, spanning a latitudinal range from 53.5°N to almost 64°S, and also digitized in the framework of ERA-CLIM. In these records, the pilot balloon ascents reach altitudes up to 20,500 m MSL, with a median height reached of 4,500 m MSL. The kite ascents reach maximum heights of 4,870 m MSL, with a median of 2,165 m MSL. Drifting registering balloons reached a maximum height of 14,700 m MSL, with the median being 6,645 m MSL.

Figure 5 depicts the global distribution of the location of all inventoried moving upper-air data. The best coverage can be seen in the Atlantic basin. Most of the observations, particularly the regular west–east transects, stem from the German Atlantic expedition of 1925–27 but also from observations made on board of merchant ships and during other scientific cruises. The positions in the top-right corner north of eastern Siberia represent data from the Norwegian north polar expedition of 1918–25, and those in the southeastern Pacific/Southern Ocean and along the Antarctic coastline are from the U.S. military Operation Highjump in 1946–47. Finally, the data points in central Europe correspond to some manned balloon rides going back to 1888.

EXAMPLES OF USE.

Apart from the use for generating data or validating products such as surface-based reanalyses or statistical reconstructions (Brohan et al. 2012), important insights on individual events or for individual stations can often be gained from analyzing the data directly. In the following, we show such an application to several weather extremes by making use of the many pilot balloon wind and radiosonde stations in India and surrounding regions in the ERA-CLIM and CHUAN upper-air datasets.

Two major cyclones and a rainstorm in India (1927–52). De et al. (2005) have listed major cyclones in the northern Indian Ocean in the twentieth century in their Table 7. Figures 6a,b show observed winds at different altitudes (depending on data availability) together with 20CR geopotential height (GPH) fields on the closely corresponding pressure levels for two of these major cyclones on days close to the maximum intensity of the storms: 31 October 1927 (Fig. 6a) and 24 October 1949 (Fig. 6b). For 1949, additional radiosonde GPH observations from CHUAN are available. The upper-air analysis of the 1927 storm is only possible with the new ERA-CLIM data. For the storm of 1949, a much more comprehensive analysis is possible with the additional ERA-CLIM data than with the CHUAN and IGRA data alone.

During the cyclone of 29 October–3 November 1927 (Fig. 6a), 300 human lives were lost and 6,000 cattle perished in the coastal region of Nellore, Andhrah Pradesh (De et al. 2005). At 0000 ± 0300 UTC 31 October 1927, the center of the low pressure system was located about 400 km southeast of the coastline of the Indian states of Andhra Pradesh and Orissa, according to 20CR. The reanalysis shows a central GPH at 800 hPa of less than 1,980 geopotential meters (gpm). The 2,000-m MSL observed ERA-CLIM wind vectors fit relatively well with expected wind directions from the 20CR GPH field in the larger region. Observed wind speeds at this altitude reach magnitudes of 18–20 m s^{-1} in southern India, close to the strong gale-force surface winds in the region of 79 km h^{-1} (~22 m s^{-1}) reported in De et al. (2005). 20CR, on the other hand, seems to underestimate the wind speeds at 800 hPa: a rough calculation of the geostrophic wind speed in the region of the two stations with the strongest winds in Fig. 6a from the 20CR GPH field gives only 11.5 m s^{-1}, with stronger winds of >20 m s^{-1} modeled only in an annular zone closer to the cyclone center.

During the cyclone of 24 October 1949 (Fig. 6b), 750 lives were lost and 30,000 cattle perished in the region of Machilipatnam, Andhrah Pradesh. According to De et al. (2005), hurricane-force winds of 130 km h^{-1} (~36 m s^{-1}) occurred at the surface. The cyclone center in the reanalysis is again located in the Gulf of Bengal but farther south than in 1927. As for 1927, observed upper-wind directions agree relatively well with those expected from the 20CR GPH field. However, 20CR suggests even weaker GPH gradients (at 850 hPa in this case) over the Indian subcontinent than in the first case, corresponding to geostrophic wind speeds of clearly less than 20 m s^{-1}. In this case, also the upper-air wind observations do not give

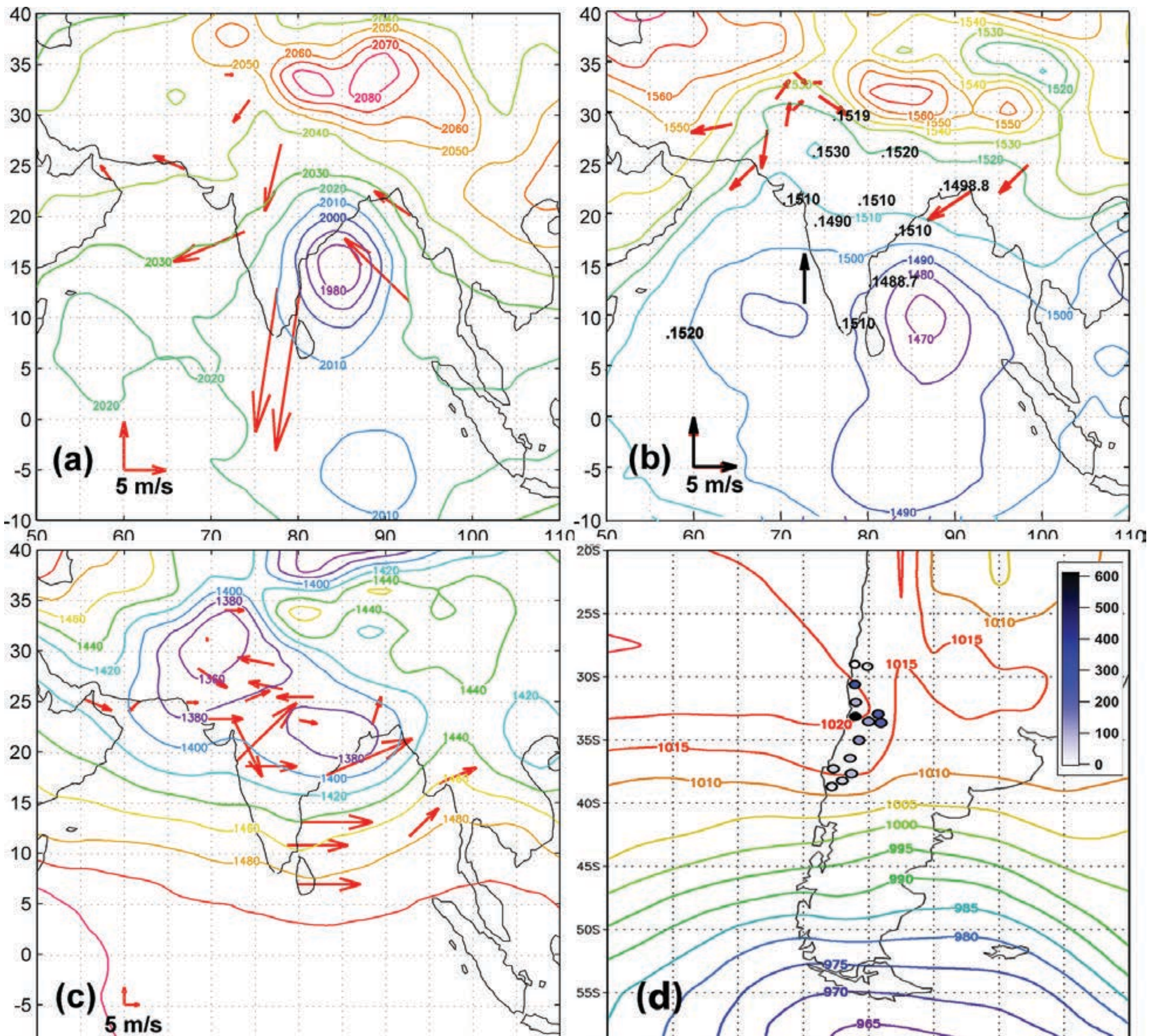

Fig. 6. (a)–(c) ERA-CLIM and CHUAN pilot balloon wind observations (red/black wind vectors) and CHUAN radiosonde GPH observations (black numbers), together with 20CR GPH fields (contour lines), displayed for two major cyclone events in the northern Indian Ocean region (1927 and 1949) and one major rainstorm event affecting the west coast of India in Jul 1941 (according to De et al. 2005): (a) 2,000-m MSL wind and 800-hPa GPH at 0000 ± 0300 UTC 31 Oct 1927; (b) 1,524-m (1,500-m) MSL ERA-CLIM (CHUAN) wind and 850-hPa GPH at 0000 ± 0300 UTC 24 Oct 1949 and observed 850-hPa CHUAN radiosonde GPH from 1500 ± 0100 UTC 23 Oct 1949; and (c) 1,500-m MSL wind and 850-hPa GPH at 0000 ± 0300 UTC 2 Jul 1941. (d) ERA-CLIM-observed 3-day precipitation sums (filled circles; m^{-2}), together with the NNR sea level pressure field (0000 UTC 20 Aug 1953; contour lines), displayed for a heavy rainfall event between 30° and 38°S in Chile on 19–21 Aug 1953.

a direct indication of very strong winds: no values above 5 m s^{-1} were observed at 1,500 m MSL in the larger region, although there are admittedly no observations available from the Indian east coast, close to the supposed location of the cyclone. Upper-air GPH observations from radiosondes are available from CHUAN. These display relatively strong differences from the reanalysis for some stations, suggesting that the GPH field in 20CR may not be very well constrained, but do not alone imply very strong geostrophic winds on the east coast either.

Another extreme event in India was a major widespread rain event with maximum intensity on 2 July 1941 that caused severe flooding along large parts of the Indian west coast (Table 6 in De et al. 2005). Figure 6c depicts the respective ERA-CLIM wind observations at 1,500 m MSL together with the 20CR 850-hPa GPH field.

20CR shows a deep low (central GPH < 1,360 gpm), located in northern Pakistan, with a secondary, slightly less intense cyclonic center over northeastern India. This configuration led to an intense westerly flow directed straight toward the western coastal mountain range of India and strong orographic lifting there. By and large, the direction of observed upper-wind vectors and 20CR GPH field agrees again quite well. Even though the GPH gradients in 20CR are relatively strong (note the doubled contour interval compared to Figs. 6a,b), the corresponding geostrophic winds of ~10 m s^{-1} are less intense than the very strong observed upper winds in western India (states of Maharashtra and Gujarat, up to 25 m s^{-1}). The agreement is better for the even higher observed and modeled wind speeds appearing along the east coast (up to 30 m s^{-1} observed; up to 28 m s^{-1} from 20CR).

A heavy rainfall event in Chile (1953). On 19–21 August 1953, heavy rainfalls occurred in Chile between 30° and 38°S. Figure 6d displays 3-day precipitation sums for that period from the newly digitized Chilean ERA-CLIM surface stations together with the sea level pressure field at 0000 UTC 20 August 1953 from NNR. Note that some of the observational parameters digitized in the framework of ERA-CLIM, such as surface precipitation as shown here, and other surface parameters, such as soil temperature, maximum and minimum temperature, evaporation, and humidity in general, are not assimilated into reanalyses at the moment but may be useful for reanalysis validation in the future.

The NNR GPH field displays an intense low south of Cape Horn (central pressure < 965 hPa) and a well-developed southeastern Pacific subtropical high west of northern Chile (central pressure > 1,025 hPa). This led to a strong pressure gradient between the two systems, connected to a strong westerly flow directed straight toward the Andes Mountains south of 37.5°S. The relatively strong lee trough east of the central Chilean Andes, leading to a westerly to southwesterly flow in central Chile, possibly contributed to the enhanced transport of moist air into the region affected by the heavy precipitation.

CONCLUSIONS AND OUTLOOK. We have given an overview of the ERA-CLIM historical surface and upper-air data rescue activities in the framework of the EU FP7 project ERA-CLIM. The main purpose of these activities was (and will be in the follow-up project; see below) to provide data for new reanalyses, which will produce continuous, global, three-dimensional estimates of the atmospheric circulation consistent with observations. Various reanalysis experiments have already been or are still being conducted at ECMWF to demonstrate the usefulness of the new data for improving reanalysis quality in certain regions of the world (Dee et al. 2014). Many of the ERA-CLIM surface observations have been assimilated in a new reanalysis of the twentieth century, ERA-20C, which will become available to the public in summer 2014. ERA-20C uses a version of the ECMWF atmospheric model especially prepared for climate applications (Hersbach et al. 2013) and assimilates surface pressure and marine wind observations from ISPD and the International Comprehensive Ocean–Atmosphere Data Set (ICOADS) in addition to those recovered in ERA-CLIM (Poli et al. 2013). The assimilation of these data into ERA-20C and other reanalyses will produce valuable feedback information to the observations community; such information might be used to produce a "corrected" version of the ERA-CLIM and CHUAN datasets. The ERA-CLIM upper-air data provide an independent reference for the validation of other products such as 20CR (e.g., Brönnimann and Stickler 2013). Also, observation errors can be estimated directly from the observations (Wartenburger et al. 2013). Additionally, a homogenization of the upper-air data is being undertaken at the University of Vienna, also a partner in ERA-CLIM, as far as this is possible with the often very short and irregular historical time series.

The data will be made freely available via the project website (www.era-clim.eu), which will also link to the metadatabase containing the complete listing of all inventoried records. The upper-air data (Stickler et al. 2014) are also available online (at http://doi.pangaea.de/10.1594/PANGAEA.821222). We have also demonstrated the usefulness of the newly available data for analyzing extreme weather events in the pre-1958 period. Ultimately these data will help improve our ability to produce extended climate reanalyses based on the entire instrumental record (Dee et al. 2014).

The digitized surface pressure and temperature data have been submitted to the ISPD and the International Surface Temperature Initiative. To the extent possible, the digitized upper-air data will be homogenized by the University of Vienna project partners. New ERA-CLIM productions at ECMWF, including ERA-20C, will make use of the data. The digitization of the cataloged, historical data will continue in the framework of ERA-CLIM2, the follow-up project to ERA-CLIM, which started in January 2014.

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REFERENCES

Allan, R., P. Brohan, G. P. Compo, R. Stone, J. Luterbacher, and S. Brönnimann, 2011: The International Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative. *Bull. Amer. Meteor. Soc.,* **92,** 1421–1425, doi:10.1175/2011BAMS3218.1.

Berson, A., 1910: *Bericht über die aerologische Expedition des Königlichen Aeronautischen Observatoriums nach Ostafrika im Jahre 1908*. Vieweg, 119 pp.

Brohan, P., R. Allan, E. Freeman, D. Wheeler, C. Wilkinson, and F. Williamson, 2012: Constraining the temperature history of the past millennium using early instrumental observations. *Climate Past,* **8,** 1551–1563, doi:10.5194/cp-8-1551-2012.

Brönnimann, S., and A. Stickler, 2013: Aerological observations in the tropics in the early twentieth century. *Meteor. Z.,* **22,** 349–358, doi:10.1127/0941-2948/2013/0458.

Compo, G. P., and Coauthors, 2011: The Twentieth Century Reanalysis project. *Quart. J. Roy. Meteor. Soc.,* **137,** 1–28, doi:10.1002/qj.776.

De, U. S., R. K. Dube, and G. S. Prakasa Rao, 2005: Extreme weather events over India in the last 100 years. *J. Indian, Geophys. Union,* **9,** 173–187.

Dee, D. P., M. Balmaseda, G. Balsamo, R. Engelen, A. J. Simmons, and J.-N. Thépaut, 2014: Toward a consistent reanalysis of the climate system. *Bull. Amer. Meteor. Soc.,* in press, doi:10.1175/BAMS-D-13-00043.1.

de Quervain, A., P.-L. Mercanton, and A. Stolberg, 1920: *Ergebnisse der Schweizerischen Grönlandexpedition 1912-1913.* Kommission für Veröffentlichungen der Schweizerischen Naturforschenden Gesellschaft, 402 pp.

Durre, I., R. S. Vose, and D. B. Wuertz, 2006: Overview of the Integrated Global Radiosonde Archive. *J. Climate,* **19,** 53–68, doi:10.1175/JCLI3594.1.

Ebita, A., and Coauthors, 2011: The Japanese 55-year Reanalysis "JRA-55": An interim report. *SOLA,* **7,** 149–152, doi:10.2151/sola.2011-038.

Grimminger, G., and W. C. Haines, 1939: *Meteorological Results of the Byrd Antarctic Expeditions 1928-30, 1933-35; Tables.* Monthly Weather Review Supplement, Vol. 41, U.S. Weather Bureau, 377 pp.

Hersbach, H., C. Peubey, A. Simmons, P. Poli, and D. Dee, 2013: ERA-20CM: A twentieth century atmospheric model ensemble. ECMWF ERA Rep. 16, 44 pp.

Hobbs, W. H., and S. P. Fergusson, 1931: *Reports of the Greenland Expeditions of the University of Michigan. Part I: Aërology, Expeditions of 1926 and 1927-29.* University of Michigan Press, 259 pp.

Holzapfel, R., W. Kopp, and K. Wegener, 1939: Meteorologie, die Ergebnisse. *Wissenschaftliche Ergebnisse der deutschen Grönland-Expedition Alfred Wegener 1929 und 1930/1931,* Vol. 4, K. Wegener, Ed., Brockhaus, 32–469.

Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.,* **82,** 247–268, doi:10.1175/1520-0477(2001)0822.3.CO;2.

Kuhlbrodt, E., and J. Reger, 1933: Die aerologischen Methoden und das Aerologische Beobachtungsmaterial. *Deutsche Atlantische Expedition auf dem Forschungsschiff „Meteor", Wissenschaftliche Ergebnisse,* Vol. 15, A. Defant, Ed., de Gruyter, 1–305.

Meteorological Services of Canada, 1940: *Canadian Polar Year Expeditions 1932-33: Meterorology: Cape Hope's Advance Coppermine Chesterfield Inlet Meanook,* Vol. 1, Patenaude, 452 pp.

Morozova, A. L., and M. A. Valente, 2012: Homogenization of Portuguese long-term temperature data series: Lisbon, Coimbra and Porto. *Earth Syst. Sci. Data,* **4,** 187–213, doi:10.5194/essd-4-187-2012.

Poli, P., and Coauthors, 2013: The data assimilation system and initial performance evaluation of the ECMWF pilot reanalysis of the 20th-century assimilating surface observations only (ERA-20C). ECMWF ERA Rep. 14, 59 pp.

Ramella-Pralungo, L., L. Haimberger, A. Stickler, and S. Brönnimann, 2014: A global radiosonde and tracked balloon archive on 16 pressure levels (GRASP) back to 1905—Part 1: Merging and interpolation to 00:00 and 12:00 GMT. *Earth Syst. Sci. Data,* **6,** 185-200, doi:10.5194/essd-6-185-200-2014.

Saha, S., and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. *Bull. Amer. Meteor. Soc.,* **91,** 1015–1057, doi:10.1175/2010BAMS3001.1.

Stickler, A., and Coauthors, 2010: The Comprehensive Historical Upper Air Network. *Bull. Amer. Meteor. Soc.,* **91,** 741–751, doi:10.1175/2009BAMS2852.1.

——, and Coauthors: 2014: Description of the ERA-CLIM historical upper-air data. *Earth Syst. Sci. Data,* **6,** 29–48, doi:10.5194/essd-6-29-2014.

Süring, R., 2013: Report by A. Berson about the aerological expedition of the Royal Aeronautic Observatory to East Africa in 1908. *Meteor. Z.,* **22,** 343–348, doi:10.1127/0941-2948/2013/0494.

Sverdrup, H. U., 1933a: The Norwegian north polar expedition with the "Maud" 1918–1925: Scientific results: Vol. 2, meteorology: Part I: Discussion. Geofysisk Institutt Bergen Rep., 331 pp.

——, 1933b: The Norwegian north polar expedition with the "Maud" 1918–1925: Scientific results: Vol. 3: Meteorology: Part II: Tables. Geofysisk Institutt Bergen Rep., 577 pp.

Thorne, P. W., and Coauthors, 2011: Guiding the creation of a comprehensive surface temperature resource for twenty-first-century climate science. *Bull. Amer. Meteor. Soc.,* **92,** ES40–ES47, doi:10.1175/2011BAMS3124.1.

Uppala, S. M., and Coauthors, 2005: The ERA-40 Re-Analysis. *Quart. J. Roy. Meteor. Soc.,* **131,** 2961–3012, doi:10.1256/qj.04.176.

Wartenburger, R., S. Brönnimann, and A. Stickler, 2013: Observation errors in early historical upper-air observations. *J. Geophys. Res. Atmos.,* **118,** 12 012–12 028, doi:10.1002/2013JD020156.

THE CONCEPT OF ESSENTIAL CLIMATE VARIABLES IN SUPPORT OF CLIMATE RESEARCH, APPLICATIONS, AND POLICY

by Stephan Bojinski, Michel Verstraete, Thomas C. Peterson, Carolin Richter, Adrian Simmons, and Michael Zemp

Described is the concept of Essential Climate Variables developed under the Global Climate Observing System for a range of applications, as well as to provide an empirical basis for understanding past, current, and possible future climate variability and change.

Observations are fundamental to advancing scientific understanding of climate (Doherty et al. 2009; Shapiro et al. 2010) and delivering the vetted, timely, and purposeful climate information needed to support decision making in many sectors. Observations and monitoring are key elements of the emerging Global Framework for Climate Services (WMO 2011a) and more generally support climate research, the assessment of climate change, and the development of policy responses (Fig. 1). For these purposes, observational datasets in general need to be traceable to quality standards, be readily interpretable and freely available, and cover sufficiently long periods: for example, the 30 years traditionally used for calculating climate normals (WMO 2011b). Transparency in the generation of climate datasets is

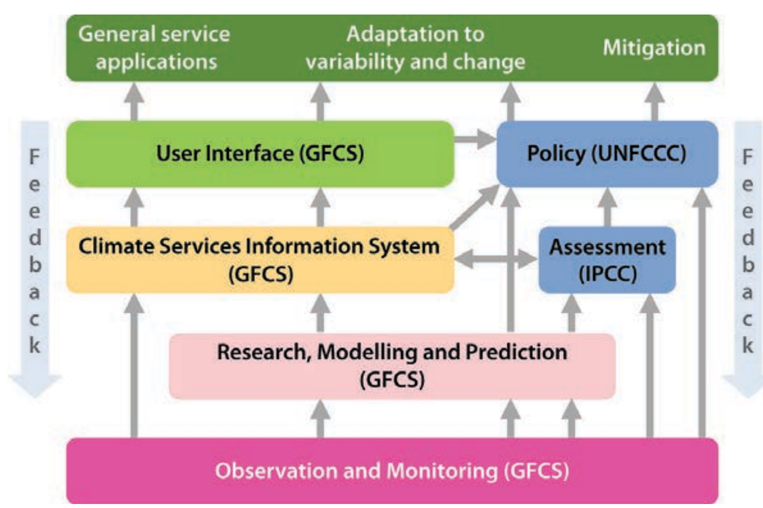

Fig. 1. The role of observation within the Global Framework for Climate Services (GFCS) and in support of research; the assessment of climate change, in particular as undertaken by the IPCC; and the development and implementation of policy responses, in particular under the UNFCCC. Gray arrows denote the main directions of flow of climate data and derived information. Feedback for system improvement flows mainly in the opposite direction. The GFCS includes a substantial capacity-development component that underlies all illustrated components. Adapted from WMO (2009, 2011a).

essential for ensuring the credibility of the climate record (UN 2012).

In the 1990s, gaps in knowledge of climate and declining core observational networks in many countries (Houghton et al. 2012) led to calls for systematic observation of a limited set of critical variables. To provide guidance, the Global Climate Observing System (GCOS) program developed the concept of "essential climate variables" (ECVs), which has since been broadly adopted in science and policy circles.

In this article, we define the ECV concept and describe its provenance, scientific rationale and uptake. We also discuss challenges and opportunities concerning the ECV concept and its possible evolution, in particular with regard to the GCOS-led process of assessment, adequacy, and implementation of global observing systems for climate.

WHAT ARE THE ECVS? An ECV is a physical, chemical, or biological variable or a group of linked variables that critically contributes to the characterization of Earth's climate. ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to guide mitigation and adaptation measures, to assess risks and enable attribution of climatic events to underlying causes, and to underpin climate services. The current list of ECVs is specified in GCOS (2010a) (all GCOS reports are available at www.wmo.int/pages/prog/gcos/index.php?name=Publications) and reproduced in Table 1.

More than variables: The ECV concept. The ECVs must not be understood as a select group of stand-alone variables; they are part of a wider concept (Fig. 2). ECVs are identified based on the following criteria:

- Relevance: The variable is critical for characterizing the climate system and its changes.
- Feasibility: Observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods.
- Cost effectiveness: Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

To make practical use of the ECVs, guidance and best practices are needed to enable and support the generation of high-quality, traceable ECV data records (see details in Fig. 2). The ECV concept accommodates mixed or changing observing system technologies and is therefore conducive to meeting user needs for information over the long term. It helps distil a complex field into a manageable list of priorities and related actions (GCOS 2010a).

PROVENANCE. Some 20 years ago, the international community began exploring a more coordinated approach to observing climate on a global scale. The GCOS program, founded in 1992 by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organisation (IOC/UNESCO), the United Nations Environment Programme (UNEP), and the International Council for Science (ICSU), was mandated to define objectives and recommend coordinated action for a global observing system for climate, building on and enhancing existing systems (GCOS 1995; Houghton et al. 2012). The initial plan called for a system based on (i) fundamental scientific priorities and (ii) prioritized observational requirements, informed by scientific and technical progress and evolving user needs. It identified "principal observations" to be addressed by a set of space missions, noting earlier work in support of short-term climate predictions (NRC 1994).

Priorities were further elaborated by exploring which physical variables or combination of variables would be most suitable for long-term climate monitoring (Karl 1996, and references therein; Trenberth 1995). Observational priorities were formulated recognizing the capabilities of current or expected observing systems.

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Table 1. The essential climate variables (for qualifying details, see GCOS 2010a).

Atmospheric	Surface:[a]	Air temperature, wind speed and direction, water vapor, pressure, precipitation, surface radiation budget
	Upper air:[b]	Temperature, wind speed and direction, water vapor, cloud properties, Earth radiation budget (including solar irradiance)
	Composition:	Carbon dioxide, methane, other long-lived greenhouse gases,[c] ozone and aerosol supported by their precursors[d]
Oceanic	Surface:[e]	Sea surface temperature, sea surface salinity, sea level, sea state, sea ice, surface current, ocean color, carbon dioxide partial pressure, ocean acidity, phytoplankton
	Subsurface:	Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers
Terrestrial		River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire disturbance, soil moisture

[a] Including measurements at standardized but globally varying heights in close proximity to the surface.

[b] Up to the stratopause.

[c] Including N_2O, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), SF_6, and perfluorocarbons (PFCs).

[d] In particular NO_2, SO_2, HCHO, and CO.

[e] Including measurements within the surface mixed layer, usually within the upper 15 m.

Subsequently, the international terrestrial community identified "key variables" describing the biosphere, hydrosphere, and cryosphere (GCOS 1997) based on measurement practicality and the priority for climate. These variables were deemed the minimal set for which data records were absolutely necessary, recognizing that other, "secondary" variables were also important for context or interpretation.

The expression "essential climate variables" was first introduced in GCOS (2003), spanning the atmospheric, oceanic, and terrestrial domains. In their response to this report, parties (signatory states) of the United Nations Framework Convention on Climate Change (UNFCCC) emphasized the principle of free and unrestricted exchange for ECV datasets, adopted an expanded set of GCOS climate monitoring principles, and requested the GCOS program to plan implementation (UNFCCC 2004).

Subsequent reporting and planning, starting with the first implementation plan (GCOS 2004), used

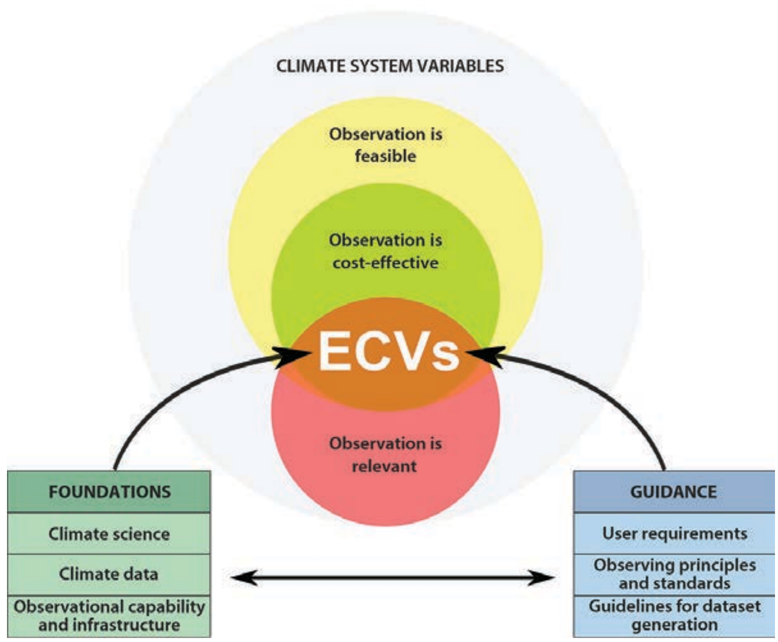

Fig. 2. Schematic of the ECV concept: knowing existing climate-relevant observing capabilities, climate datasets, and the level of scientific understanding of the climate system are the foundations (lower-left box) necessary for selecting the ECVs from a pool of climate system variables. In addition, guidance is needed to make practical use of the ECVs (lower-right box): user requirements capture the data quality needs of science, services, and policy; climate-specific principles guide the operation of observing systems and infrastructure; and guidelines facilitate the transparent generation of ECV data records. The latter address the availability of metadata, provisions for data curation and distribution, and the need for quality assessment and peer review.

the ECVs as a guiding framework. Indicative requirements for accuracy, spatial and temporal resolution and other characteristics of ECV datasets were specified for satellite-based datasets (GCOS 2006, 2011). Guidelines were also developed for generating ECV data records in general, emphasizing the importance of calibration and validation, documentation, and self and independent assessments (GCOS 2010b). The 20 climate monitoring principles, developed based on the original set of 10 adopted by the UNFCCC in 1999, provide guidance for observing system operations (GCOS 2010a).

UPTAKE. Science and policy circles have widely endorsed the ECV concept. The parties to the UNFCCC acknowledged the need to act upon the plans for implementation (GCOS 2004, 2010a). Guidelines for their reporting on national programs contributing to global climate observation are structured along the ECVs (UNFCCC 2008). In its planning of global observation for weather, water, and climate applications, WMO addresses the ECVs and recognizes GCOS assessment and planning documents as statements of guidance.

The ECVs have been identified as a key element of the observations and monitoring pillar of the GFCS (WMO 2011a). European regulation on initial operation of environmental services within the Copernicus initiative [formerly Global Monitoring for Environment and Security (GMES)] builds upon the ECVs for its climate service component (European Union 2010). Some countries use the ECV concept to identify national climate observing networks and data records and to improve the legal and financial basis for continuity (Seiz and Foppa 2007).

Satellite agencies have responded strongly to the concept, through the Committee on Earth Observation Satellites (CEOS 2008) and more recently through the broadly developed Architecture for Climate Monitoring from Space (Dowell et al. 2013). ESA launched the Climate Change Initiative aimed at the generation of satellite-derived ECV datasets based on historical data holdings (Hollmann et al. 2013; ESA 2013). EUMETSAT (2011) responded by deriving ECV records (Schulz et al. 2009) and, along with the Japan Meteorological Agency, by reprocessing wind and other data from their geostationary satellites. Agencies from the United States, China, and other countries engage in related initiatives such as the Global Space-Based Inter-Calibration System (GSICS; Hewison et al. 2013) and the Sustained, Coordinated Processing of Environmental Satellite Data for Climate Monitoring (SCOPE-CM; Lattanzio et al. 2013).

Annual statements on the state of the global climate are now structured around the ECVs (Blunden and Arndt 2013; this reference includes a range of average multidecadal ECV time series and a brief account of ECV provenance), and so is a recent report on global climate events during the decade of 2001–10 (WMO 2013). Most of the essential needs for sustained observation identified by the World Climate Research Programme (WCRP) and enabling the work of the Intergovernmental Panel on Climate Change (IPCC) are based on the ECVs (Doherty et al. 2009). Systematic assessment and evaluation of ECV datasets at the international level is a general need, and has begun (WCRP 2011; Stubenrauch et al. 2013).

In summary, identifying ECVs and associated guidance has encouraged scientists and observing system operators to put more focus on these variables. It has stimulated the engagement of national and international organizations and funding agencies to support work on the variables. It has also helped many nations to make commitments to support systematic, sustained climate records.

The variable-based approach has been adopted more broadly as a basis for prioritized requirements setting and focused, coordinated action. In particular, the ocean and biodiversity communities have identified essential ocean variables (UNESCO 2012) and essential biodiversity variables (Pereira et al. 2013). Furthermore, many ECVs may also be useful for addressing applications that are not directly climate related: for instance, in support of other societal benefit areas of the Global Earth Observation System of Systems (GEOSS; e.g., Hollingsworth et al. 2005).

DISCUSSION AND ILLUSTRATION. The ECV concept supports observing system planning, network design and operation, and climate dataset generation but is not without its challenges.

Observing system planning and resourcing. By their very nature, ECVs (or quantities closely related to them from which ECV datasets can be derived) must be observed as a matter of priority, in a way that meets requirements. The ECV concept guides the specification of observing networks and archiving systems and the arrangements for monitoring their performance. However, meeting climate standards implies continuing investments in instrumentation and in the generation, validation, and intercomparison of datasets. Existing infrastructure, often in support of weather forecasting, may need upgrading to meet the more exacting needs of some climate applications. Despite progress in recent years, much of the global infrastructure for acquiring and archiving climate observations and for delivering related climate datasets and services remains fragile and incomplete (GCOS 2009; WMO 2011a).

Further optimizing the design of an integrated global climate observing system remains important (Trenberth et al. 2012). The GCOS program recognized a hierarchy of observational networks and systems, comprising comprehensive, baseline, and reference networks (Houghton et al. 2012; Seidel et al. 2009) based on assumptions of spatial sampling needs (e.g., Peterson et al. 1997). However, a more systematic approach is needed to observing system design studies, including impact experiments, using guidance from the numerical weather prediction community (WMO 2012) and recognizing that many observations will continue to serve both weather and climate purposes. Such studies have to take account of intrinsic climate variability and limits to predictability (Meehl et al. 2009; Hoskins 2013).

Many research activities are important to systematic ECV observation since (i) they provide supplemental observations, (ii) they seek better ways of meeting targets for accuracy, and (iii) they pioneer capabilities to measure new variables. Yet, projects or systems based on research funding are generally not designed for transition to sustained monitoring of variables globally and over long time periods, often leading to partial, haphazard, intermittent coverage (Keeling 1998; Nisbet 2007; Wunsch et al. 2013). Recognition of variables as ECVs has helped alleviate issues and foster transition of research-based observational activities into a more sustained framework (e.g., WGMS 2008; ICOS 2013).

Generating ECV datasets. Long-term instrument-level datasets, such as satellite-based "fundamental climate data records" (calibrated datasets at nominal instrument-specific resolution), are the critical basis for generating ECV datasets. Many steps need to be carefully considered, for which GCOS (2010b) provides general guidance. Quality assessment and peer review of datasets are very important (see sidebar). Providers of climate datasets should, where possible, meet community-specific needs for representing data, such as in suitable gridded formats with information on uncertainty to facilitate model–observation comparisons (Gómez-Navarro et al. 2012).

Reanalysis. Reprocessing past observations of atmosphere, ocean and land using data assimilation methods as developed for numerical weather prediction and seasonal forecasting has become an important information source on recent climate variations (Dee et al. 2014) and for assessing climate models (Gleckler et al. 2008). Such reanalysis is both a consumer and, as featured in the State of the Climate report (Blunden and Arndt 2013), a contributor to ECV datasets. The European interim global reanalysis from 1979 (ERA-Interim), for example, provides datasets for atmospheric surface and upper-air ECVs and other ECVs such as ozone and ocean-wave state, but its assimilating model uses specified sea surface temperatures, sea ice concentrations, and various land surface fields and radiative gas distributions. Extension to provide analysis of atmospheric composition ECVs is discussed by Dee et al. (2014). Ocean and land reanalyses provide datasets on variables such as subsurface ocean temperature and soil moisture but in turn utilize meteorological forcing fields from atmospheric reanalysis or other sources. Capability for analyzing other domains continues to improve, as shown by Balmaseda et al. (2013) for ocean reanalysis, and, with further development of coupled data assimilation, the number of reanalysis-based ECV datasets is expected to rise.

The quality and applicability of the comprehensive ECV datasets provided by reanalysis vary geographically, with height, over time, and from one variable to another and can be difficult to quantify. For example, Compo et al. (2011) use ensemble data assimilation to estimate uncertainty associated with flow-dependent predictability, but this does not obviate the need for additional, observation-related diagnostic information that supplements gridded reanalysis datasets (Dee et al. 2011). Comparison of an ECV dataset from reanalysis with an alternative derived directly from observations as outlined in the sidebar can provide reassurance as to the quality of both (Simmons et al. 2010).

Examples for terrestrial ECVs. Many terrestrial ECVs, such as river runoff and soil moisture, are of vital direct societal importance, and many are inherently more heterogeneous than their atmospheric and oceanic counterparts. Establishing international coordination and measurement standards has been more difficult for terrestrial than for other ECVs. Yet, progress has been made (GCOS 2009) and benefits of designating variables as ECVs have been realized. Two examples are briefly discussed.

FAPAR. The fraction of absorbed photosynthetically active radiation (FAPAR) is a measure of the productivity of the continental biosphere and thus of utmost interest. Identification as an ECV helped focus the attention of the scientific community, and multiple teams developed methods to retrieve values from remote sensing in the solar spectral range. This led to the generation of multiple datasets, stimulated the organization of field campaigns to acquire in situ measurements, and prompted CEOS to address discrepancies in the context of its calibration and validation working group. Efforts to harmonize FAPAR datasets are ongoing (e.g., Ceccherini et al. 2013). Yet, despite intense research and sustained efforts to establish standards and best practices (e.g., on validation; Widlowski 2010), no institution has proposed to be or been identified to serve as the central point of contact for the worldwide compilation, archiving, and distribution of FAPAR datasets.

Glaciers and ice caps. Glaciers and ice caps have been recognized as an ECV since they are clear indicators of climate change and important contributors to

BUILDING ECV DATASETS FOR CLIMATE MONITORING

One key application to be addressed by the ECVs is climate monitoring: that is, assessing climate variability and change using long time series of observations. Building an ECV dataset suitable for monitoring is generally complex. Typical steps are as follows:

Assembling the data. This first step may be straightforward for some in situ ECV datasets where the observations have already been taken and assembled as part of large data collections (e.g., surface water vapor; Willett et al. 2013). Alternately, it may involve analyzing satellite observations spanning a decade or more to extract broad-scale representations of upper-air temperature (Spencer and Christy 1990). Some ECVs, such as the long-lived and strongly infrared-absorbing perfluorocarbons (PFCs), may require new observing instrumentation for accurate monitoring (Miller et al. 2008) that can also be used to extend the ECV record into the past by assessing archived gas (Mühle et al. 2010). Additionally, ECVs such as surface temperature may require searching archives and digitizing historical paper records to improve spatial or temporal coverage (e.g., Peterson and Griffiths 1997).

Adjusting data to account for inhomogeneities. In addition to spurious errors in individual data values, which good quality-control tests can remove, there are few long-term ECV observations that do not suffer from inhomogeneities unrelated to climate. Examples are drifts in satellite orbits over time and changes in observing practice: for example, ship-based sea surface temperature observations changed from putting thermometers in buckets that had been tossed overboard to haul up water from the surface of the ocean to thermometers being placed in engine cooling water intakes, which, for large ships, are typically located 5–15 m below the surface (Kent and Kaplan 2006). There exist many techniques to adjust climate time series data to account for such artificial inhomogeneities (e.g., Aguilar et al. 2003).

Real-time updates. Regular updates of an ECV dataset are required if the dataset is to be used for monitoring changes in the ECV. Operationally updating a dataset is a very different process requiring different skill sets than conducting the homogeneity research. It also marks the transition from research to operations.

Postproduction quality assurance. There are many different aspects to this stage. It often involves scrutinizing the data to assess particular characteristics of the ECV record. For example, for surface temperature, do rural stations indicate the same changes as the dataset as a whole (e.g., Peterson et al. 1999)? Or do permafrost temperatures increase when winter air temperatures increase (e.g., Smith et al. 2012)? Did sensor degradation or aerosols from volcanic eruptions artificially change a satellite-derived leaf area index (Los et al. 2000)? This stage also involves evaluating real-time updates to correct for other errors: for example, in the metadata (Lawrimore et al. 2011).

Documentation and transparency. As the IPCC Fourth Assessment Report states, "scientists usually submit their research findings to the scrutiny of their peers, which includes disclosing the methods that they use, so their results can be checked through replication by other scientists" (Le Treut et al. 2007, p. 95). However, given the central role that ECVs are increasingly having in monitoring the global climate, a higher level of transparency is generally expected to ensure credibility, as stated in the introduction. For example, rather than just providing the data and describing the algorithms used to produce the dataset, providing public access to the actual computer code used to make the ECV dataset is now part of what is considered best practice (Bates and Privette 2012).

More than one dataset per ECV is required. After over a decade of producing an upper-air temperature record, with a series of successive improvements (Christy et al. 2003), another group undertook the creation of a satellite-derived record for this ECV. In the process of producing their version (Mears et al. 2003), they uncovered an error in the first group's adjustment to account for satellite drift, an error that changed the sign of the adjustment (Thorne et al. 2010). This example illustrates that the best proof of quality is having several independent groups producing their own versions of ECV datasets, ideally using different methodologies, as this would help quantify the structural uncertainty in the ECV records as well as provide an objective, empirical corroboration of the results (Folland et al. 2006).

Monitoring the ECV. A key need is to understand how the ECVs are changing. The State of the Climate report (Blunden and Arndt 2013) provides an annual reference based on a large community effort that assesses change for many ECVs and other climatic variables. Not only does coauthoring that paper provide an opportunity for scientists to update their results annually but, because the report includes multiple alternative ECV datasets wherever possible, it allows ready comparison of the results of different groups.

global sea level changes, regional water cycles, and local hazards. Changes in glacier length, area, volume, and mass are the key variables. Records date back to the seventeenth century and transnational compilations of such data were initiated in the late nineteenth century (WGMS 2008). Loss of glacier mass due to surface air temperature and precipitation changes contributes an estimated 30% to total observed sea level change (Gardner et al. 2013), underscoring the need to understand and observe the physical interplay of atmospheric, ocean, and terrestrial ECVs.

Recognizing glaciers as an ECV has helped secure sustained funding for the World Glacier Monitoring Service (WGMS) and additional funding for capacity building promoting the resumption of systematic observation in some countries (MeteoSwiss 2013). Terminology standards and best observational practices have also been developed (Cogley et al. 2011; Zemp et al. 2013).

Essential fluxes. It has been proposed that fluxes (e.g., of energy, water, carbon) be included in the ECV list, mainly since they are essential for understanding the cyclical processes of the climate system. Fluxes can sometimes be derived from measured gradients of ECVs: for example, by analyzing atmospheric humidity profiles obtained from soundings or by eddy covariance measurements of trace gases. Generally and especially at large scales, however, fluxes are not directly observable. They are inferred from a combination of observations, model simulations and assumptions about the permeability of interfaces: for example, for estimating the net flux of methane over permafrost areas using biogeochemical models and observations (Zhang et al. 2012). Clearer focus on how to quantify these fluxes and to agree on consistent terminology and measurement principles should improve the description of exchange processes at interfaces and facilitate understanding of biogeochemical cycles.

Consistency of the ECV list. Consistently applying the selection criteria for ECVs has been a challenge because of their diversity. This extends to adding or removing variables: the importance of many other variables has long been recognized (GCOS 1997 identified as many as 70 key variables to characterize land surfaces), but their adoption as ECVs has been hampered by other considerations: for instance, in the case of land surface temperature, complexity of interpretation, and limited utility for climate monitoring. Some variables have been initially "carried over" as ECVs because of their historical importance and availability, though they might not have been selected in the absence of such a legacy (e.g., chlorophyll concentration in the top ocean layer).

Diverse requirements. Different observation requirements for the same ECV from different application communities need to be recognized and reconciled, where possible. For example, numerical weather forecasting and seasonal prediction require near-real-time access to observations of atmospheric and surface variables to optimally predict (possibly extreme) events. Some of the variables may also be of great interest for climate adaptation or trend studies. These applications have quite different requirements for spatial and temporal resolution, timeliness of data delivery, absolute accuracy, measurement stability, and length of data record.

Similarly, requirements for biological variables such as the leaf area index, which measures the surface of leaf material in plant canopies, are quite different for constraining a climate model than for managing agricultural systems against a regional climate change backdrop: horizontal resolution of global climate models is generally on the order of 50 km and would require a leaf area index dataset at this order of spatial resolution, whereas, for agricultural management, details on a resolution as fine as 1 km or less may be necessary. In the same vein, requirements for measuring air temperature for estimating urban heat stress differ from those for quantifying multidecadal trends in regional temperature.

Moreover, the thematic separation of ECVs into three geophysical domains has led to the setting of somewhat incompatible specifications for variables that are physically linked. For example, in GCOS (2011) observational requirements set for the ECV "surface albedo" (a joint property of the land and the overlying atmosphere; GCOS 2007; Lattanzio et al. 2013) are not compatible with the requirements set for aerosols and clouds, which are drivers of the atmospheric radiative properties. Such inconsistencies require further attention.

HOW SHOULD THE ECV CONCEPT EVOLVE? The ECV concept has proven useful to scientists, observing system operators, program planners, and policymakers, but issues related to consistency, data curation, resources, requirements, and review of the ECV concept have been identified. How should the concept evolve over the coming decades? The following paragraphs discuss additional drivers for a progressive evolution and a process for managing it.

Data curation and stewardship. Many communities have risen to the challenge of long-term data management and stewardship. They have designed and built unique, worldwide facilities to preserve essential heritage information in their respective fields, including seed banks to preserve biodiversity (Fowler 2008), powerful data infrastructures to support large-scale particle physics experiments (Bird 2011), and the UNESCO world cultural heritage record (UNESCO 1972). Such facilities require institutional commitments, agreements on sharing resources, and common data management standards.

Elements of a global infrastructure for climate dataset curation and stewardship are in place, partly based on data centers recognized within the ICSU World Data System (ICSU 2013). However, the data policies of many providers still prevent free and open data access to ECV datasets, despite progress in response to repeated calls for change (Uhlir et al. 2009). Intellectual property issues that compromise open access to climate records (Nelson 2009) should be overcome by introducing data identifiers [e.g., digital object identifiers (DOIs)] as standard practice, thus incentivizing data sharing through recognition of authorship. Restrictions stemming from a perceived commercial or strategic value of climate data are more difficult to resolve.

Also, although the Global Observing Systems Information Center data portal hosted by the U.S. National Climatic Data Center (www.gosic.org) facilitates discovery and access to ECV products, gaps remain in providing single access points to well-documented datasets in common data formats for the complete range of ECVs. New cost-sharing arrangements to ensure long-term stewardship (e.g., by levying observation activities) should be explored.

Broadening the Earth observation basis. Over the coming decade, wider availability of low-cost sensor technology will contribute to higher spatial and temporal sampling of the near-surface environment (e.g., through deployment in urban environments, transport vehicles, drones, or "citizen observations"). Although tradeoffs between data quality and volume will have to be made, such observations could be beneficial for tracking impacts of or exposure to climatic and other environmental hazards and thereby help building ECV datasets. Broad deployment of observing technology could also raise public awareness of environmental monitoring and eventually lead to smarter environmental decision making.

Beyond climate. Today's climate models still have limited representations of the biogeochemical cycles (notably carbon). Decades from now, global models of the Earth system will likely simulate agricultural and industrial production, transport, consumption, economic flows, and demography. Socioeconomic variables such as gross domestic product, rate of mortality, disease incidence, and transport routes would be considered to be as essential as the current set of physical, chemical, and biological variables. Data on some of these socioeconomic variables are already needed to model anthropogenic emissions of greenhouse gases and other pollutants, to monitor and control other environmental risks, and to provide climate services. Much more will be needed as modeling capabilities expand. Progress in data assimilation and observation technology is expected to go hand in hand with this development. Climate and environment information will become increasingly important for understanding and predicting the evolution of markets and influence financial strategies. These communities may evolve from mere customers of information to also directly supporting the generation, archiving and distribution of basic data.

Process. Given its broad uptake, further development of the ECV concept needs to be well managed, based on regular reviews and updates of guidance. The process that has been developed by the GCOS program involves a variable-based assessment and implementation cycle that is shown in generic, schematic form in Fig. 3. It builds on the existence of an identified pool of climate-relevant variables: the ECVs and other variables that are candidates for consideration as ECVs depending on relevance, feasibility, and cost effectiveness. The cycle comprises the following:

- *assessment of adequacy* of observing systems, ECV datasets, and scientific and technological developments (the *foundations* in Fig. 2), with implications for the list of ECVs;
- *implementation* planning based on an updated set of ECVs and guidance material (*guidance* in Fig. 2), identifying the required actions related to observing system design, dataset generation, and data stewardship; and
- responses by the agents for implementation (e.g., observing system operators), seen most immediately by users in the *generation and exploitation of datasets* that underpin products, user applications, and services.

Figure 3 goes beyond current GCOS practice in also recognizing that some data records should be designated to be part of the climate heritage record and should be preserved in dedicated archives. The heritage record should include datasets that have been superseded by new science or technology; where possible, these datasets should be maintained in parallel with new observations during a period of overlap sufficient to ensure a traceable record, and some should be continued for as long as they usefully serve as a baseline for climate assessments.

The GCOS reporting and planning documents that result from the assessment and implementation cycle are based on broad community engagement. This involves scientific workshops that draw on lessons learned from the IPCC assessment process; scrutiny by its cosponsored expert panels for atmosphere, ocean, and land (Houghton et al. 2012); open public review and response to comments; and formal acceptance by the Steering Committee for GCOS, to which members are appointed by the program sponsors. The process gains legitimacy through acceptance by the sponsors, the parties to the UNFCCC, and others, including the various national and international agents for implementation without whom progress could not be made.

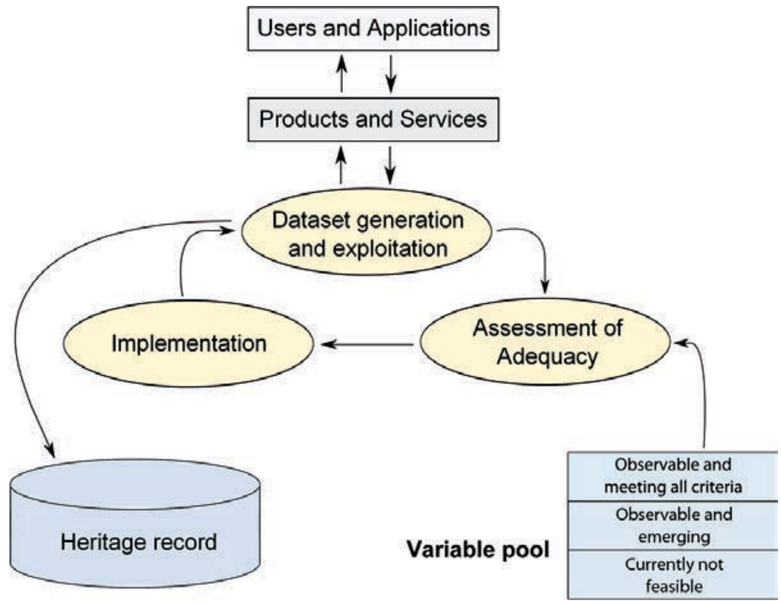

Fig. 3. Process for regularly reviewing the ECV concept, under GCOS program auspices. At around 6-yr intervals, the adequacy of climate observations, datasets, and related infrastructure (e.g., archives) is assessed, using feedback from ECV dataset users. Updated plans for implementation should result in improved ECV dataset generation and exploitation. Each iteration of the cycle considers emerging climate system variables in the "variable pool" for their relevance, feasibility, and cost effectiveness of observation. This cycle is generic and could serve as a model for other observation types.

The essential character of the ECV list has been one of its strengths, calling for prudence in its expansion. The roughly 6-yr period adopted by GCOS for the cycle illustrated in Fig. 3 has tended to follow that of the IPCC assessment reports, though arguably it should be a little longer. Observation requirements for ECV datasets must recognize the needs of the range of applications. Although a holistic approach to setting them is desirable, the user requirements for ECV datasets will not in general be consistent among each other. In any case, GCOS requirements are of indicative nature, and more refined user requirements have to be developed for specific observing missions and dataset generation initiatives (e.g., Hollmann et al. 2013).

Addition of fluxes and socioeconomic variables to the ECVs would require a departure from the current distinction by geophysical domains. Questions to address would include, for example, whether the GCOS climate monitoring principles can be straightforwardly adapted to guide observing systems for socioeconomic parameters or whether the same principles for dataset documentation and reprocessing can be applied to datasets describing population and wealth distribution. Ways of defining and presenting the ECV concept will have to evolve.

IN CONCLUSION. The ECV concept has been successful and should continue to guide the observation community in enabling evidence-based climate monitoring, science, and services. The ECV concept addresses public demands for transparency in environmental decision making (UN 2012; Major Groups 2012). We nevertheless realize the limits to rationality and objectivity in such decisions (Nilsson and Dalkmann 2001), even if optimal observation-based evidence (e.g., for environmental degradation) is available.

The ECV concept is flexible vis à vis changing priorities, application needs, and scientific and technological innovation. Priorities remain essential; the ECV concept has provided guidance in this regard. It may serve as a blueprint for communities of practice in other societal benefit areas of the GEOSS as they assess evolving data needs and required actions for observing the Earth system.

The climate community at large is invited to participate in the discussion of further evolution of the ECV concept. The process lives from consensus and active participation. Strong connections to those involved in climate research, particularly through the WCRP, and in applications remain essential. The GCOS program has already begun a new assessment phase, which will draw in part on conclusions drawn from the IPCC Fifth Assessment Report. Based on its evaluation of progress and adequacy, the next issue of the implementation plan for the global observing system for climate will be developed for 2016. The GCOS Secretariat (gcosjpo@wmo.int) should be contacted for further information.

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REFERENCES

Aguilar, E., I. Auer, M. Brunet, T. C. Peterson, and J. Wieringa, 2003: *Guidelines on climate metadata and homogenization*. WCDMP Tech Doc. 53, WMO Tech. Doc. 1186, 55 pp.

Balmaseda, M. A., K. Mogensen, and A. T. Weaver, 2013: Evaluation of the ECMWF ocean reanalysis system ORAS4. *Quart. J. Roy. Meteor. Soc.,* **139,** 1132–1161, doi:10.1002/qj.2063.

Bates, J. J., and J. L. Privette, 2012: A maturity model for assessing the completeness of climate data records. *Eos, Trans. Amer. Geophys. Union,* **93,** 441, doi:10.1029/2012EO440006.

Bird, I., 2011: Computing for the Large Hadron Collider. *Ann. Rev. Nucl. Part. Sci.,* **61,** 99–118, doi:10.1146/annurev-nucl-102010-130059.

Blunden, J., and D. S. Arndt, Eds., 2013: State of the climate in 2012. *Bull. Amer. Meteor. Soc.,* **94** (Suppl.), S1–S238, doi:10.1175/2013BAMSStateoftheClimate.1.

Ceccherini, G., N. Gobron, and M. Robustelli, 2013: Harmonization of fraction of absorbed photosynthetically active radiation (FAPAR) from Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and Medium Resolution Imaging Spectrometer Instrument (MERIS). *Remote Sens.,* **5,** 3357–3376, doi:10.3390/rs5073357.

CEOS, 2008: The Earth observation handbook: Climate change special edition 2008. ESA Rep. SP-1315, 265 pp.

Christy, J. R., R. W. Spencer, W. B. Norris, W. D. Braswell, and D. E. Parker, 2003: Error estimates of version 5.0 of MSU-AMSU bulk atmospheric temperatures. *J. Atmos. Oceanic Technol.,* **20,** 613–629, doi:10.1175/1520-0426(2003)202.0.CO;2.

Cogley, J. G., and Coauthors, 2011: Glossary of glacier mass balance and related terms. IHP-VII Hydrology Tech. Doc. 86, IACS Contribution 2, 114 pp. [Available online at http://unesdoc.unesco.org/images/0019/001925/192525e.pdf.]

Compo, G. P., and Coauthors, 2011: The Twentieth Century Reanalysis Project. *Quart. J. Roy. Meteor. Soc.,* **137,** 1–28, doi:10.1002/qj.776.

Dee, D. P., E. Källén, A. J. Simmons, and L. Haimberger, 2011: Comments on "Reanalyses suitable for characterizing long-term trends." *Bull. Amer. Meteor. Soc.,* **92,** 65–70, doi:10.1175/2010BAMS3070.1.

——, M. Balmaseda, G. Balsamo, R. Engelen, A. J. Simmons, and J.-N. Thépaut, 2014: Toward a consistent reanalysis of the climate system. *Bull. Amer. Meteor. Soc.,* in press, doi:10.1175/BAMS-D-13-00043.1.

Doherty, S. J., and Coauthors, 2009: Lessons learned from the IPCC AR4: Scientific developments needed to understand, predict, and respond to climate change. *Bull. Amer. Meteor. Soc.,* **90,** 497–513, doi:10.1175/2008BAMS2643.1.

Dowell, M., and Coauthors, 2013: Strategy towards an architecture for climate monitoring from space. CEOS, WMO, and CGMS Rep., 39 pp. [Available online at www.wmo.int/pages/prog/sat/documents/ARCH_strategy-climate-architecture-space.pdf.]

ESA, 2013: Response by ESA to GCOS—Results of the climate change initiative requirements analysis. ESA Rep. CCI-PRGM-EOPS-TN-13-0008, 84 pp. [Available online at http://46.137.76.174/?q=webfm_send/80.]

EUMETSAT, 2011: EUMETSAT strategy: A global operational satellite agency at the heart of Europe. EUMETSAT Rep. COR.02-v1, 28 pp. [Available online at www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=PDF_BR_COR02_EN&RevisionSelectionMethod=LatestReleased&Rendition=Web.]

European Union, 2010: Regulation (EU) No 911/2010 of the European Parliament and of the council of 22 September 2010 on the European Earth monitoring programme (GMES) and its initial operations (2011 to 2013). EU Doc. OJ L 276, 20.10.2010, 10 pp [Available online at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32010R0911:EN:NOT.]

Folland, C. K., D. Parker, R. W. Reynolds, S. C. Sherwood, and P. W. Thorne, 2006: What measures can be taken to improve the understanding of observed changes? Temperature trends in the lower atmosphere: Steps for understanding and reconciling differences, T. R. Karl et al., Eds., Climate Change Science Program and the Subcommittee on Global Change Research Rep., 119–128.

Fowler, C., 2008: The Svalbard Global Seed Vault: Securing the future for agriculture. Global Crop Diversity Trust Rep., 28 pp. [Available online at www.croptrust.org/documents/Svalbard%20opening/New%20EMBARGOED-Global%20Crop%20Diversity%20Trust%20Svalbard%20Paper.pdf.]

Gardner, A. S., and Coauthors, 2013: A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science,* **340,** 852–857, doi:10.1126/science.1234532.

GCOS, 1995: Plan for the Global Climate Observing System, version 1.0. GCOS Rep. 14, 49 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/gcos-14.pdf.]

——, 1997: GCOS/GTOS plan for terrestrial climate-related observations, version 2.0. GCOS Rep. 32, 130 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/gcos-32.pdf.]

——, 2003: Second report on the adequacy of the global observing systems for climate in support of the UNFCCC. GCOS Rep. 82, 85 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/gcos-82_2AR.pdf.]

——, 2004: Implementation plan for the global observing system for climate in support of the UNFCCC. GCOS Rep. 92, 153 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/gcos-92_GIP.pdf.]

——, 2006: Systematic Observation requirements for satellite-based products for climate: Supplemental details to the satellite-based component of the implementation plan for the global observing system for climate in support of the UNFCCC. GCOS Rep. 107, 103 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/gcos-107.pdf.]

——, 2007: GCOS AOPC/TOPC Joint Working Group on Land-Surface/Atmosphere Issues (WG-LSA). GCOS Tech. Paper 1, 18 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/GCOS-TP1.pdf.]

——, 2009: Progress report on the implementation of the global observing system for climate in support of the UNFCCC 2004-2008. GCOS Rep. 129, 112 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/gcos-129.pdf.]

——, 2010a: Implementation plan for the global observing system for climate in support of the UNFCCC (2010 update). GCOS Rep. 138, 186 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf.]

——, 2010b: Guideline for the generation of datasets and products meeting GCOS requirements. GCOS Rep. 143, 12 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/gcos-143.pdf.]

——, 2011: Systematic observation requirements for satellite-based products for climate 2011 update: Supplemental details to the satellite-based component of the "Implementation plan for the global observing system for climate in support of the UNFCCC (2010 update). GCOS Rep. 154, 138 pp. [Available online at www.wmo.int/pages/prog/gcos/Publications/gcos-154.pdf.]

Gleckler, P., K. E. Taylor, and C. Doutriaux, 2008: Performance metrics for climate models. *J. Geophys. Res.,* **113,** D06104, doi:10.1029/2007JD008972.

Gómez-Navarro, J. J., J. P. Montávez, S. Jerez, P. Jiménez-Guerrero, and E. Zorita, 2012: What is the role of the observational dataset in the evaluation and scoring of climate models? *Geophys. Res. Lett.,* **39,** L24701, doi:10.1029/2012GL054206.

Hewison, T., X. Wu, F. Yu, Y. Tahara, X. Hu, D. Kim, and M. Koenig, 2013: GSICS inter-calibration of infrared channels of geostationary imagers using Metop/IASI. *IEEE Trans. Geosci. Remote Sens.,* **51,** 1160–1170, doi:10.1109/TGRS.2013.2238544.

Hollingsworth, A., and Coauthors, 2005: The transformation of earth-system observations into information of socio-economic value in GEOSS. *Quart. J. Roy. Meteor. Soc.,* **131,** 3493–3512, doi:10.1256/qj.05.181.

Hollmann, R., and Coauthors, 2013: The ESA climate change initiative: Satellite data records for essential climate variables. *Bull. Amer. Meteor. Soc.,* **94,** 1541–1552, doi:10.1175/BAMS-D-11-00254.1.

Hoskins, B., 2013: The potential for skill across the range of the seamless weather-climate prediction problem: A stimulus for our science. *Quart. J. Roy. Meteor. Soc.,* **139,** 573–584, doi:10.1002/qj.1991.

Houghton, J., J. Townshend, K. Dawson, P. Mason, J. Zillman, and A. Simmons, 2012: The GCOS at 20 years: the origin, achievement and future development of the Global Climate Observing System. *Weather,* **67** (9), doi:10.1002/wea.1964.

ICOS, 2013: A European infrastructure dedicated to high-precision monitoring of greenhouse gas fluxes. Integrated Carbon Observation System Rep., 4 pp. [Available online at www.icos-infrastructure.eu/sites/icos-infrastructure-transition.eu/files/Icos4pager_06_03_2012.pdf.]

ICSU, 2013: ICSU World Data System Implementation Plan 2014–2018, 10 pp, [Available online at www.icsu-wds.org/files/wds-strategic-plan-201420132018.]

Karl, T., Ed., 1996: *Long-Term Climate Monitoring by the Global Climate Observing System.* Kluwer Academic, 518 pp.

Keeling, C. D., 1998: Rewards and penalties of monitoring the earth. *Annu. Rev. Energy Environ.,* **23,** 25–82, doi:10.1146/annurev.energy.23.1.25.

Kent, E. C., and A. Kaplan, 2006: Toward estimating climatic trends in SST. Part III: Systematic biases. *J. Atmos. Oceanic Technol.,* **23,** 487–500, doi:10.1175/JTECH1845.1.

Lattanzio, A., and Coauthors, 2013: Land surface albedo from geostationary satellites: A multiagency collaboration within SCOPE-CM. *Bull. Amer. Meteor. Soc.,* **94,** 205–214, doi:10.1175/BAMS-D-11-00230.1.

Lawrimore, J. H., M. J. Menne, B. E. Gleason, C. N. Williams, D. B. Wuertz, R. S. Vose, and J. Rennie, 2011: An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3. *J. Geophys. Res.,* **116,** D19121, doi:10.1029/2011JD016187.

Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson, and M. Prather, 2007: Historical overview of climate change. *Climate Change 2007: The Physical Science Basis,* S. Solomon et al., Eds., Cambridge University Press, 93–127.

Los, S. O., and Coauthors, 2000: A global 9-yr biophysical land surface dataset from NOAA AVHRR data. *J. Hydrometeor.,* **1,** 183–199, doi:10.1175/1525-7541(2000)0012.0.CO;2.

Major Groups, 2012: Rio+20 common statement. Stakeholder Forum of the Earth Summit 2012 Discussion Paper, 2 pp. [Available online at www.stakeholderforum.org/fileadmin/files/Major%20Groups%20common%20statement.pdf.]

Mears, C. A., M. C. Schabel, and F. J. Wentz, 2003: A reanalysis of the MSU channel 2 tropospheric temperature record. *J. Climate,* **16,** 3650–3664, doi:10.1175/1520-0442(2003)0162.0.CO;2.

Meehl, G. A., and Coauthors, 2009: Decadal prediction: Can it be skillful? *Bull. Amer. Meteor. Soc.,* **90,** 1467–1485, doi:10.1175/2009BAMS2778.1.

MeteoSwiss, cited 2013: Capacity Building and Twinning for Climate Observing Systems (CATCOS)—Glacier monitoring. [Available online at www.meteoschweiz.admin.ch/web/en/meteoswiss/international_affairs/international_projects/CATCOS/terrestrial_domain.html.]

Miller, B. R., R. F. Weiss, P. K. Salmeh, T. Tanhua, B. R. Greally, J. Mühle, and P. G. Simmonds, 2008: Medusa: A sample preconcentration and GC/MS detector system for in situ measurements of atmospheric trace halocarbons, hydrocarbons, and sulfur compounds. *Anal. Chem.,* **80,** 1536–1545, doi:10.1021/ac702084k.

Mühle, J., A. L. and Coauthors, 2010: Perfluorocarbons in the global atmosphere: Tetrafluoromethane, hexafluoroethane, and octafluoropropane. *Atmos. Chem. Phys.,* **10,** 5145–5164, doi:10.5194/acp-10-5145-2010.

Nelson, B., 2009: Empty archives. *Nature,* **461,** 160–163, doi:10.1038/461160a.

Nilsson, M., and H. Dalkmann, 2001: Decision making and strategic environmental assessment. *J. Environ. Assess. Policy Manage.,* **3,** 305, doi:10.1142/S1464333201000728.

Nisbet, E., 2007: Cinderella science. *Nature,* **450,** 789–790, doi:10.1038/450789a.

NRC, 1994: *Ocean-Atmosphere Observations Supporting Short-Term Climate Predictions.* National Academy Press, 51 pp.

Pereira, H. M., and Coauthors, 2013: Essential biodiversity variables. *Science,* **339,** 277–278, doi:10.1126/science.1229931.

Peterson, T. C., and J. F. Griffiths, 1997: Historical African data. *Bull. Amer. Meteor. Soc.,* **78,** 2869–2872.

——, H. Daan, and P. Jones, 1997: Initial selection of a GCOS surface network. *Bull. Amer. Meteor. Soc.,* **78,** 2145–2152, doi:10.1175/1520-0477(1997)0782.0.CO;2.

——, K. P. Gallo, J. Lawrimore, T. W. Owen, A. Huang, and D. A. McKittrick, 1999: Global rural temperature trends. *Geophys. Res. Lett.,* **26,** 329–332, doi:10.1029/1998GL900322.

Schulz, J., and Coauthors, 2009: Operational climate monitoring from space: The EUMETSAT Satellite Application Facility on Climate Monitoring (CM-SAF). *Atmos. Chem. Phys.,* **9,** 1687–1709, doi:10.5194/acp-9-1687-2009.

Seidel, D. J., and Coauthors, 2009: Reference upper-air observations for climate: Rationale, progress, and plans. *Bull. Amer. Meteor. Soc.,* **90,** 361–369, doi:10.1175/2008BAMS2540.1.

Seiz, G., and N. Foppa, 2007: National Climate Observing System. MeteoSwiss and ProClim Rep., 95 pp. [Available online at www.meteosuisse.admin.ch/web/en/meteoswiss/international_affairs/gcos/uebersicht_klimabeobachtung/nationales_klimabeobachtungssystem.Par.0027.DownloadFile.tmp/nationalclimateobservingsystem.pdf.]

Shapiro, M., and Coauthors, 2010: An Earth-system prediction initiative for the twenty-first century. *Bull. Amer. Meteor. Soc.,* **91,** 1377–1388, doi:10.1175/2010BAMS2944.1.

Simmons, A. J., K. M. Willett, P. D. Jones, P. W. Thorne, and D. P. Dee, 2010: Low-frequency variations in surface atmospheric humidity, temperature, and precipitation: Inferences from reanalyses and monthly gridded observational data sets. *J. Geophys. Res.,* **115,** D01110, doi:10.1029/2009JD012442.

Smith, S. L., J. Throop, and A. G. Lewkowicz, 2012: Recent changes in climate and permafrost temperatures at forested and polar desert sites in northern Canada. *Can. J. Earth Sci.,* **49,** 914–924, doi:10.1139/e2012-019.

Spencer, R. W., and J. R. Christy, 1990: Precise monitoring of global temperature trends from satellites. *Science,* **247,** 1558–1562, doi:10.1126/science.247.4950.1558.

Stubenrauch, C. J., and Coauthors, 2013: Assessment of global cloud datasets from satellites: Project and database initiated by the GEWEX Radiation Panel. *Bull. Amer. Meteor. Soc.,* **94,** 1031–1049, doi:10.1175/BAMS-D-12-00117.1.

Thorne, P. W., J. R. Lanzante, T. C. Peterson, D. J. Seidel, and K. P. Shine, 2010: Tropospheric temperature trends: History of an ongoing controversy. *Wiley Interdiscip. Rev.: Climate Change,* **2,** 66–88, doi:10.1002/wcc.80.

Trenberth, K. E., 1995: Long-term climate monitoring by the Global Climate Observing System. *Climatic Change,* **31,** 163–180, doi:10.1007/BF01095144.

——, and Coauthors, 2012: Challenges of a sustained climate observing system. *Climate Science for Serving Society: Research, Modelling and Prediction Priorities,* J. W. Hurrell and G. Asrar, Eds., Springer, 485 pp.

Uhlir, P. F., R. S. Chen, J. I. Gabrynowicz, and K. Janssen, 2009: Towards implementation of the Global Earth Observation System of Systems data sharing principles. *J. Space Law,* **35,** 201–290.

UN, cited 2012: The future we want. – United Nations General Assembly Resolution 66/288. [Available online at http://sustainabledevelopment.un.org/futurewewant.html.]

UNESCO, 1972: Convention concerning the protection of the world cultural and natural heritage. United Nations Educational, Scientific and Cultural Organisation, 17 pp. [Available online at http://whc.unesco.org/archive/convention-en.pdf.]

——, 2012: Framework for ocean observing. Task Team for an Integrated Framework for Sustained Ocean Observing Rep. INF-1284, 28 pp, doi:10.5270/OceanObs09-FOO.

UNFCCC, 2004: Global observing systems for climate. Report of the Conference of the Parties on its ninth session, held at Milan from 1 to 12 December 2003, 20–22 [Available online at http://unfccc.int/resource/docs/cop9/06a01.pdf#page=20.]

——, 2008: Reporting on global observing systems for climate. Report of the Conference of the Parties on its thirteenth session, held in Bali from 3 to 15 December 2007, 17 pp. [Available online at http://unfccc.int/resource/docs/2007/cop13/eng/06a02.pdf#page=1.

WCRP, 2011: Report of WOAP Workshop on Evaluation of Satellite-Related Global Climate Datasets. WCRP Informal Rep. 33/2011, GCOS-153, 44 pp. [Available online at http://wcrp-climate.org/documents/ECV_Wksp_WCRP_Report.pdf.]

WGMS, 2008: Global glacier changes: Facts and figures. UNEP World Glacier Monitoring Service Rep., 88 pp. [Available online at www.grid.unep.ch/glaciers/pdfs/glaciers.pdf.]

Widlowski, J.-L., 2010: On the bias of instantaneous FAPAR estimates in open-canopy forests. *Agric. For. Meteor.,* **150,** 1501–1522, doi:10.1016/j.agrformet.2010.07.011.

Willett, K. M., C. N. Williams Jr., R. J. H. Dunn, P. W. Thorne, S. Bell, M. de Podesta, P. D. Jones, and D. E. Parker, 2013: HadISDH: an updateable land surface specific humidity product for climate monitoring. *Climate Past,* **9,** 657–677, doi:10.5194/cp-9-657-2013.

WMO, 2009: Better climate information for a better future. WMO Secretariat World Climate Conference-3 Third Announcement, 24 pp.

——, 2011a: Climate knowledge for action: A global framework for climate services, empowering the most vulnerable. World Meteorological Organization Rep. 1065, 248 pp. [Available online at www.wmo.int/hlt-gfcs/downloads/HLT_book_full.pdf.]

——, 2011b: Guide to climatological practices. World Meteorological Organization Rep. 100, 117 pp. [Available online at www.wmo.int/pages/prog/wcp/ccl/documents/WMO_100_en.pdf.]

——, 2012: WMO Integrated Global Observing System—Final report of the Fifth WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction. WMO Tech. Rep. 2012-1, 25 pp. [Available online at www.wmo.int/pages/prog/www/OSY/Meetings/NWP5_Sedona2012/Final_Report.pdf.]

——, 2013: The global climate 2001–2010: A decade of climate extremes. World Meteorological Organization Rep. 1103, 119 pp. [Available online at http://library.wmo.int/pmb_ged/wmo_1103_en.pdf.]

Wunsch, C., R. W. Schmitt, and D. J. Baker, 2013: Climate change as an intergenerational problem. *Proc. Natl. Acad. Sci. USA,* **110,** 4435–4436, doi:10.1073/pnas.1302536110.

Zemp, M., and Coauthors, 2013: Reanalysing glacier mass balance measurement series. *Cryosphere,* **7,** 1227–1245, doi:10.5194/tc-7-1227-2013.

Zhang Y., T. Sachs, C. Li, and J. Boike, 2012. Upscaling methane fluxes from closed chambers to eddy covariance based on a permafrost biogeochemistry integrated model. *Global Change Biol.,* **18,** 1428–1440, doi:10.1111/j.1365-2486.2011.02587.x.

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AWARENESS OF BOTH TYPE 1 AND 2 ERRORS IN CLIMATE SCIENCE AND ASSESSMENT

BY WILLIAM R. L. ANDEREGG, ELIZABETH S. CALLAWAY, MAXWELL T. BOYKOFF, GARY YOHE, AND TERRY L. ROOT

Climate science and assessment sometimes focus too strongly on avoiding false-positive errors, when false-negative errors may be just as important.

The concept of risk has been identified as a fundamental framing to the analysis of what to do about anthropogenic climate change, unanimously agreed to by the signatories of the United Nations Framework Convention on Climate Change (Pachauri and Reisinger 2007; Alley et al. 2007; National Research Council 2011). Stephen Schneider was essential in drafting the language in the summary for policymakers of the Synthesis Report of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) that has framed the risk-based approach to climate change: "Responding to climate change involves an iterative risk management process that includes both mitigation and adaptation" (Pachauri and Reisinger 2007, p. 64). At its core, risk assessment and risk management involve determination of probabilities and consequences of outcomes, both of which have uncertainties associated with them. Scientists aim to illuminate the full probability distributions of risks by accounting for the full range of different types of uncertainties while avoiding potential errors in causal relationships via statistical forms of inference, such as hypothesis testing.

Based on formal hypothesis testing in statistics, scientists typically consider two types of error (Fig. 1). Type 1 errors are a false positive: a researcher states that a specific relationship exists when in fact it does not. Type 1 errors are typically avoided in hypothesis testing by determining whether a p value, roughly the probability that a result could be obtained by chance alone, falls below a predetermined threshold. A 5% p value cutoff has become scientific convention in many fields of the natural sciences, but it could, in

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	Null hypothesis is TRUE	Null hypothesis is FALSE
Reject null hypothesis	Type I Error (False positive)	Correct outcome! (True positive)
Fail to reject null hypothesis	Correct outcome! (True negative)	Type II Error (False negative)

Fig. 1. Graphical representation of type 1 and type 2 errors.

theory, be selected to be a different threshold. This false positive comes in the form of a double negative (type 1 errors mean incorrectly rejecting the null hypothesis that a relationship does not exist). Type 2 errors are the reverse: a null hypothesis would not be rejected despite being false—a false negative on the hypothesis that no relationship exists. A scientist says *no* relationship exists when, in fact, one exists; but again, the *p* value threshold for making such a claim is, in fact, arbitrary.

This statistical formulation of type 1/type 2 errors is relevant in the detection and attribution of climate change (Trenberth 2011), determining whether an observed impact or a climatic extreme event is likely to have been caused by anthropogenic climate change. Yet, type 1 and type 2 errors are also relevant to the projection of climate change and climate impacts in assessing the future scenarios' respective risks and mean and lower and upper bounds of projected climate changes/impacts from different sources (Schneider 2006). In scientific assessments such as the IPCC, scientists synthesize and weight multiple lines of evidence from diverse tools. Thus, the relative avoidance of type 1 versus type 2 errors can shape this synthesis process and the findings produced. In this case, an overestimation of a given climate impact is analogous to type 1 errors (i.e., a false positive in the magnitude of an impact), while an underestimation of the impact corresponds to type 2 errors (Schneider 2006; Brysse et al. 2013).

Recent research has suggested in a number of key attributes in climate change that scientists have "erred on the side of least drama" by underestimating changes in climate assessments (Brysse et al. 2013), effectively favoring the risk of type 2 errors to lower the chances of type 1 errors. Yet decision makers often take both type 1 and type 2 errors seriously. While many risk management and decision-making frameworks take account of and attempt to minimize the occurrence of both types of errors, available evidence suggests that recent climate science does not amply consider both types of errors, particularly in assessments.

Type 1 and type 2 errors become especially important in what has been termed "postnormal science," where risks and/or uncertainty are high in a policy-relevant issue and decisions must likely be made without complete certainty (Funtowicz and Ravetz 1993). With its dependence on the complex and chaotic coupled climate–land–ocean system, human activities, policy decisions, system inertia, and time lags, climate science and climate impacts are generally considered within these landscapes of postnormal science (Bray and von Storch 1999; Saloranta 2001). These two types of errors factor into the complex landscape of uncertainty characterization, which has been increasingly explored and utilized within the context of the IPCC (Mastrandrea et al. 2011; Moss and Schneider 2000; O'Reilly et al. 2011; Yohe and Oppenheimer 2011). Yet, careful treatment of type 2 errors can fall outside current uncertainty characterizations and it has particular relevance to climate impacts (Trenberth 2005). Failure to account for both type 1 and type 2 errors leaves a discipline or assessment processes in danger of irrelevancy, misrepresentation, and unnecessary damages to society and human well-being (Oppenheimer et al. 2007). We further explore error avoidance in the context of two prominent case studies in the Fourth Assessment Report of the IPCC.

SEA LEVEL RISE IN THE IPCC FOURTH ASSESSMENT REPORT. Sea level rise constitutes one of the most prominent and visible climate change impacts reported by the IPCC, with implications for human livelihoods and billions of dollars required for adapting, managing, and planning for sea level rise in the twenty-first century. From 1993 to 2003 sea level increased at a rate of about 3 mm yr^{-1}, which is significantly higher than the 1.8 mm yr^{-1} average increase for the twentieth century (Alley et al. 2007). Working Group I (WGI) of the IPCC attributed about half of this current increase to the melting of land ice, a dynamical and incompletely understood process that has accelerated in recent years (Bindoff et al. 2007). The melting of Greenland and Antarctic ice sheets, however, had still not been modeled with great accuracy and had, in fact, been increasing at unpredictable rates. Because ice sheet melting was accelerating quickly and in unpredictable ways, "quantitative projections of how much it would add [to sea level rise] cannot be made with confidence" (Bindoff et al. 2007, p. 409). The authors decided, given these realities, to remove sea level rise driven by ice melt from their future estimates—not because the ice was not melting but because future rates could not be projected.

More specifically, Working Group I of the Fourth Assessment Report dealt with this insufficient understanding by removing the acceleration of ice sheet melt out of its quantitative projections of the future. The summary for policymakers' table 3 of sea level rise projections includes sea level contributions from ice sheet flow held steady at the rates observed from 1993 to 2003, but they do not include a continuation of the observed acceleration of melt (Alley et al. 2007). The Fourth Assessment Report gives ranges for sea level rise by 2100 that were lower than those reported in the Third Assessment Report and the Fifth Assessment Report (Fig. 2), but it warns that "Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise" (Alley et al. 2007, p. 14); and they provided a footnote to explain why.

We highlight this example as an instance of how type 1 errors could potentially manifest in scientific assessments. Naturally, the projected range is for a future date and, while observed trends exceed the projected trends, we will not know whether any ranges were an error until that time period. Several scientists pointed out this potential type 2 error in the peer-reviewed literature is a consequence of "scientific reticence" (Hansen 2007), which includes a strong focus on avoiding type 1 errors. The limitations of consensus and dynamics of the IPCC assessment process, however, may have instead influenced this range (Oppenheimer et al. 2007; Solomon et al. 2008), as the process of determining upper and lower bounds involves integrating and weighting different sources of information and model simulations.

We analyzed a dataset of major U.S. and U.K. media outlet news coverage of the IPCC WGI report to examine whether media outlets reported the critical caveat regarding the upper bounds of sea level rise. A lack of reporting this caveat suggests that this potential type 2 error impaired effective communication of climate risks. We used published methods of media analysis on a database of seven major U.S. and U.K. newspapers (Rick et al. 2011) with articles mentioning *global warming* or *climate change*, subsampled for mentions of *sea level* from 1 February to 31 March 2007 to examine media coverage of the release of WGI report. Of the news articles in the dataset that covered the report release, 81% reported the quantitative sea level rise projections (18–59 cm), while only 31% mentioned the qualitative caveats about missing dynamical ice sheet contributions. Other studies have found that the media more often reports IPCC summaries of sea level rise, rather than individual studies (Rick et al. 2011), which indicates that the IPCC reported range matters for climate change communication and risk assessment.

A retrospective analyses of several key attributes of global warming concluded that the IPCC as an institution has tended to be generally conservative and often underestimate key characteristics of climate (Brysse et al. 2013). This arguably has led to larger (though unknown) type 2 error rates, particularly in presenting the upper bounds of climate changes and impacts that might not capture the full tails of the probability density function distribution. As we discuss in the "Conclusions" section, higher type 2 error rates may be particularly harmful in presenting the full spectrum of risk for risk assessment and management.

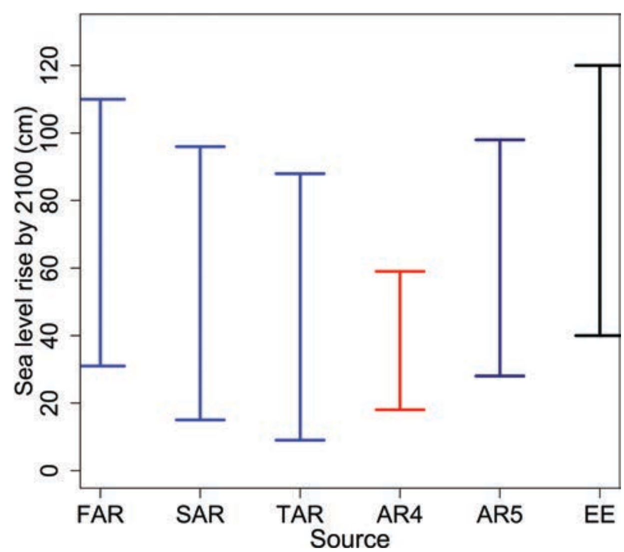

Fig. 2. Reported upper and lower bounds of global sea level rise by ca. 2100 from summary reports in the IPCC assessment reports and a recent expert elicitation analysis: (left to right) First Assessment Report (FAR; increase by 2100; Rick et al. 2011) in 1991, Second Assessment Report (SAR; increase by 2100 relative to 1990; Rick et al. 2013) in 1996, Third Assessment Report (TAR; increase by 2100 relative to 1990; Houghton et al. 2001) in 2001, Fourth Assessment Report (AR4; 5%–95% range on increase by 2090–99 relative to 1980–99, with table notation "excluding future rapid dynamical changes in ice flow"; Alley et al. 2007) in 2007, Fifth Assessment Report (AR5; 17%–83% range on increase by 2100 relative to 1985–2005; Alexander et al. 2013) in 2013, and an expert elicitation analysis (EE; 17%–83% range on increase by 2100 relative to 2000; Horton et al. 2014).

HIMALAYAN GLACIER MELT IN THE IPCC FOURTH ASSESSMENT REPORT. Known as the "third pole" for its extensive glaciers, Himalayan glaciers provide critical water resources for millions of people in India, China, and other nations. In 2010, three years following the publication of the Fourth Assessment Report, it came to light that a single section in a chapter in *Climate Change 2007: Impacts, Adaptation and Vulnerability* had overstated the rate at which glaciers were melting from the Himalayan region. Stemming from a lapse in the application of quality control and review of nonjournal literature and potentially a simple typographical error, a section in chapter 10 of *Climate Change 2007: Impacts, Adaptation and Vulnerability* mistakenly reported that glacial melt of many glaciers was possible by 2035, though the executive summary of the chapter correctly concluded, "The retreat of glaciers and permafrost in Asia in recent years is unprecedented as a consequence of warming" (Cruz et al. 2007, p. 471). While recent research has in fact shown that the majority of Himalayan glaciers *are* melting and at a rate on par with glaciers around the world (Fujita and Nuimura 2011; Kaab et al. 2012; Kargel et al. 2011), the 2035 melt date is almost certainly an overstating of melt rates (Bolch et al. 2012) and thus provides an example of a possible type 1 error.

In contrast to the sea level rise, the scientific community and media response to this potential error was substantial. In the peer-reviewed literature, the melt date was described as incorrect (Cogley et al. 2010) and some suggested that "this error . . . shredded the reputation of a large and usually rigorous international virtual institution" (Kargel et al. 2011, p. 14 709). The IPCC issued a formal statement, saying it "regret[s] the poor application of well-established IPCC procedures in this instance" (IPCC 2013, p. 1). The IPCC response emphasized that the organization has numerous processes and procedures to examine evidence and to avoid errors. These procedures had simply not been adequately followed in this case.

Did the overestimation actually damage scientific credibility of the IPCC? It is hard to know the true impact, but polling data since the incident indicates likely not. A poll conducted in June 2010 found that 14% of Americans heard in the news recently about errors in the IPCC report (Leiserowitz et al. 2013). About 5% said that these errors had decreased their trust in climate scientists, though these were largely concentrated in the "doubtful" and "dismissive" categories of respondents with relatively low trust in climate scientists prior (Leiserowitz et al. 2013).

Another set of polling data questioned a nationally representative sample of Americans concerning the Himalayan glacier error in June 2010, six months after the incident. Around 24% of the nation said they remembered hearing about recent errors, but only 4% said they thought the errors indicated scientific misconduct (J. Krosnick and B. MacInnis 2014). After a set of calculations with respondents indicating a degree of trust of climate scientists, the authors determined that the maximum theoretical upper bound of opinion change was a 5% decrease in trust of climate scientists. The actual change in the degree of trust based on longitudinal polling data from this study, however, was statistically insignificant from zero (J. Krosnick and B. MacInnis 2014). The average change of public belief in the existence of global warming across all nine sets of available polling data before and after the Himalayan glacier error and the hacking of the University of East Anglia e-mails, and thus potentially attributable to these two events, was 6%, but longitudinal analysis of public opinion over 2006–11 indicates that year-to-year fluctuations in temperature appear to have a much larger effect on public opinion (J. Krosnick and B. MacInnis 2014), which aligns with recent research documenting the direct "experiential learning" effect of temperatures on public opinion on climate change in many sections of the U.S. public (Myers et al. 2013). Taken together, the breadth of polling data since this incident indicates that a relatively small portion of Americans were aware of this controversy, that Americans have generally trusted scientists studying the environment, and that this trust did not decline following this error (J. Krosnick and B. MacInnis 2014).

CONCLUDING REMARKS. The two case studies analyzed here illustrate the intricacies and complexities in avoiding both type 1 and type 2 errors in scientific assessments. Oppenheimer and colleagues (2007) have noted that searching for consensus in an assessment process such as the IPCC can be counterproductive to risk assessment. We suggest that assessment can further institutionalize the aversion to type 1 errors and attendant risk of committing type 2 errors. Both in paradigm and procedure, the scientific method and culture prioritize type 1 error aversion (Hansson 2013) and "erring on the side of least drama" (O'Reilly et al. 2011) or "scientific reticence" (Hansen 2007), and this can be amplified by both publication bias and scientific assessment (Freudenburg and Muselli 2010; Lemons et al. 1997; O'Reilly et al. 2011). Thus, the high consequence and tails of the distribution of climate impacts, where experts may disagree on likelihood or where understanding is still limited, can often be left out or understated in the assessment process (Oppenheimer et al. 2007; Socolow 2011). As participants in the IPCC assessments, we have observed the excessive focus on avoiding type 1 errors at various stages in the assessment process, which may have worsened following the Himalayan glacier event.

Growing evidence suggests that, partly owing to this treatment of error as well as other processes, consensus scientific assessments to date are likely to underestimate climate disruptions (Brysse et al. 2013; Freudenburg and Muselli 2010; O'Reilly et al. 2011). A recent paper reviewed the suite of studies that compared past predictions with recent observations of sea level rise, surface temperature increase, melting of Arctic sea ice, permafrost thaw, and hurricane intensity and frequency. The study found that IPCC assessments of projections were on the whole largely correct or even underestimates (possible type 2 errors), and that there was little to no evidence of "alarmism" or widespread overestimates (Brysse et al. 2013). Thus, while a full accounting of the relative prevalence of type 1 versus type 2 errors is not possible (as what determines an "error" is a difficult question and future projections cannot be assessed currently), the balance of evidence indicates that potential type 2 errors may be more prevalent in assessments, such as the IPCC.

This asymmetry of treatment of error has unintended consequences. Type 2 errors can hinder communication of the full range of possible climate risks to the media, the public, and decision makers who have to justify the basis of their analyses. Thus, such errors have the potential to lead to unnecessary loss of lives, livelihoods, or economic damages. Yet, as Stephen Schneider eloquently highlighted throughout his work, high-consequence, controversial, uncertain impacts are exactly what policy makers and other stakeholders would like to know to perform risk management (National Research Council 2011; Schneider et al. 1998; Socolow 2011).

Naturally, varying situations and contexts apply different decision rules in considering type 1 versus type 2 errors, and type 1 error aversion is beneficial in certain circumstances. Moreover, uncertainty must be recognized as multifaceted and textured. As such, Brian Wynne described four kinds of uncertainty: 1) "risk"—where we know the odds, system behavior, and outcomes can be defined as well as quantified through probabilities; 2) "uncertainty"—where system parameters are known, but not the odds or probability distributions; 3) "ignorance"—risks that escape recognition; and 4) "indeterminacy"—which captures elements of the conditionality of knowledge and contextual scientific, social, and political factors (Wynne 1992). Thus, the risks through uncertainty in these conditions of postnormal science have material implications. Incomplete presentation of the full possibilities of outcomes (likelihood compounded by consequence) can lead to a lack of preparedness, loss of livelihoods or lives, and economic damage.

Error and uncertainty are inherent to all science, scientific inquiry, and policy decision making. Furthermore, various mobilizations of uncertainty and varied interpretations of risk have long played a critical part in ways of making climate change meaningful in civil society. Climate science, especially the IPCC assessments, is a considered leader in the treatment of uncertainty in a highly complex and societally relevant research field (Morgan and Mellon 2011). Thus, lessons learned in climate science regarding treatment of uncertainty and type 1/2 errors may also be applicable in other policy-relevant fields, such as medicine. While considerations of type 1 and type 2 errors sometimes fall outside the typical approach to uncertainty characterization, several steps would help better address an asymmetry of error:

- First, as part of an awareness of one's own epistemological biases, treatment of type 2 error *as error* is critical.
- Second, reporting the full range of possible outcomes, even if improbable, controversial, or poorly understood, is essential if it is "not implausible."
- Third, drawing on information from diverse sources, especially in scientific assessment such as the IPCC, can help avoid type 2 errors.
- Finally, better use of formal expert elicitation analysis can provide a full spectrum of possible impacts, supplement other data sources, and help avoid type 2 errors.

The IPCC has made progress to opening the door on some of these areas. The most recent uncertainty guidance document covers some of the abovementioned steps and states that "findings can be constructed from the perspective of minimizing false-positive (type 1) or false-negative (type 2) errors, with resultant tradeoffs in the information emphasized" (Mastrandrea et al. 2013, p. 1). Furthermore, the expert elicitation analysis literature is also expanding in its treatment of major climate system uncertainties. A recent study on sea level rise based on elicitation analysis of 90 experts estimated the range of sea level rise by 2100 at 40–120 cm (Horton et al. 2014), with upper bounds above the current IPCC "likely" range (Fig. 2).

Regardless of the future fate of the IPCC periodic reports, assessments of climate science will continue in the future and will be aimed at providing rigorous risk assessment of climate change impacts. Ultimately, awareness among climate scientists of both type 1 and type 2 errors will best advance the field and help provide accurate and nuanced risk assessment for decision makers.

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REFERENCES

Alexander, L. V., and Coauthors 2013: Summary for policymakers. *Climate Change 2013: The Physical Science Basis,* T. F. Stocker et al., Eds. Cambridge University Press, 3–29. [Available online at www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf.]

Alley, R., and Coauthors, 2007: Summary for policymakers. *Climate Change 2007: The Physical Science Basis,* S. Solomon et al., Eds., Cambridge University Press, 1–18.

Bindoff, N. L., and Coauthors, 2007: Observations: Oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis,* S. Solomon et al., Eds., Cambridge University Press, 385–432.

Bolch, T., and Coauthors, 2012: The state and fate of Himalayan glaciers. *Science,* **336,** 310–314, doi:10.1126/science.1215828.

Bray, D., and H. von Storch, 1999: Climate science: An empirical example of postnormal science. *Bull. Amer. Meteor. Soc.,* **80,** 439–455, doi:10.1175/1520-0477(1999)0802.0.CO;2.

Brysse, K., N. Oreskes, J. O'Reilly, and M. Oppenheimer, 2013: Climate change prediction: Erring on the side of least drama? *Global Environ. Change,* **1,** 327–337.

Cogley, J. G., J. S. Kargel, G. Kaser, and C. J. van der Veen, 2010: Tracking the source of glacier misinformation. *Science,* **327,** 522, doi:10.1126/science.327.5965.522-a.

Cruz, R. V., and Coauthors, 2007: Asia. *Climate Change 2007: Impacts, Adaptation and Vulnerability,* M. L. Parry et al., Eds., Cambridge University Press, 469–506.

Freudenburg, W. R., and V. Muselli, 2010: Global warming estimates, media expectations, and the asymmetry of scientific challenge. *Global Environ. Change,* **20,** 483–491, doi:10.1016/j.gloenvcha.2010.04.003.

Fujita, K., and T. Nuimura, 2011: Spatially heterogeneous wastage of Himalayan glaciers. *Proc. Natl. Acad. Sci. USA,* **108,** 142011–142014, doi:10.1073/pnas.1106242108.

Funtowicz, S. O., and J. R. Ravetz, 1993: Science for the post-normal age. *Futures,* **25,** 739–755, doi:10.1016/0016-3287(93)90022-L.

Hansen, J. E., 2007: Scientific reticence and sea level rise. *Environ. Res. Lett.,* **2,** 024002, doi:10.1088/1748-9326/2/2/024002.

Hansson, S. O., cited 2013: Risk. *The Stanford Encyclopedia of Philosophy* (winter 2012 edition). Edward N. Zalta, Ed. [Available online at http://plato.stanford.edu/archives/win2012/entries/risk/.]

Horton, B., S. Rahmstorf, S. Engelhart, and A. Kemp, 2014: Expert assessment of sea-level rise by AD 2100 and AD 2300. *Quat. Sci. Rev.,* **84,** 1–6, doi:10.1016/j.quascirev.2013.11.002.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Eds., 2001: *Climate Change 2001: The Scientific Basis.* Cambridge University Press, 881 pp.

IPCC, cited 2013: IPCC statement on the melting of Himalayan glaciers. [Available online at www.ipcc.ch/pdf/presentations/himalaya-statement-20january2010.pdf.]

Kaab, A., E. Berthier, C. Nuth, J. Gardelle, and Y. Arnaud, 2012: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature,* **488,** 495–498, doi:10.1038/nature11324.

Kargel, J. S., J. G. Cogley, G. J. Leonard, U. Haritashya, and A. Byers, 2011: Himalayan glaciers: The big picture is a montage. *Proc. Natl. Acad. Sci. USA,* **108,** 14709–14710, doi:10.1073/pnas.1111663108.

Leiserowitz, A., E. Maibach, C. Roser-Renouf, N. Smith, and E. Dawson, 2013: Climategate, public opinion, and the loss of trust. *Amer. Behav. Sci.,* **57,** 818–837.

Lemons, J., K. Shrader-Frechette, and C. Cranor, 1997: The precautionary principle: Scientific uncertainty and type I and type II errors. *Found. Sci.,* **2,** 207–236, doi:10.1023/A:1009611419680.

MacInnis, B., and J. A. Krosnick, 2014: Trust in scientists' statements about the environment and American public opinion on global warming. *New Explorations in Political Psychology.* J. A. Krosnick,

T. H. Stark, and I. A. Chiang, Eds., Psychology Press, in press.

Mastrandrea, M. D., and Coauthors, cited 2013: Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties. [Available online at www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.]

Morgan, M., and C. Mellon, 2011: Certainty, uncertainty, and climate change. *Climatic Change,* **108,** 707–721, doi:10.1007/s10584-011-0184-8.

Moss, R., and S. Schneider, 2000: Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting. *Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC,* R. Pachauri, T. Tangiguchi, and K. Tanaka, Eds., World Meteorological Organization, 33–51.

Myers, T. A., E. W. Maibach, C. Roser-Renouf, K. Akerlof, and A. A. Leiserowitz, 2013: The relationship between personal experience and belief in the reality of global warming. *Nat. Climate Change,* **3,** 343–347, doi:10.1038/nclimate1754.

National Research Council, 2011: *America's Climate Choices.* The National Academies Press, 144 pp.

Oppenheimer, M., B. C. O'Neill, M. Webster, and S. Agrawala, 2007: The limits of consensus. *Science,* **317,** 1505–1506, doi:10.1126/science.1144831.

O'Reilly, J., K. Brysse, M. Oppenheimer, and N. Oreskes, 2011: Characterizing uncertainty in expert assessments: Ozone depletion and the West Antarctic ice sheet. *Wiley Interdiscip. Rev.: Climate Change,* **2,** 728–743, doi:10.1002/wcc.135.

Pachauri, R. K., and A. Reisinger, Eds., 2007: *Climate Change 2007: Synthesis Report.* Cambridge University Press, 104 pp.

Rick, U. K., M. T. Boykoff, and R. A. Pielke Jr., 2011: Effective media reporting of sea level rise projections: 1989–2009. *Environ. Res. Lett.,* **6,** 014004, doi:10.1088/1748-9326/6/1/014004.

Saloranta, T., 2001: Post-normal science and the global climate change issue. *Climatic Change,* **50,** 395–404, doi:10.1023/A:1010636822581.

Schneider, S. H., 2006: Climate change: Do we know enough for policy action? *Sci. Eng. Ethics,* **12,** 607–636, doi:10.1007/s11948-006-0061-4.

——, B. L. Turner, and H. M. Garriga, 1998: Imaginable surprise in global change science. *J. Risk Res.,* **1,** 165–185, doi:10.1080/136698798377240.

Socolow, R., 2011: High-consequence outcomes and internal disagreements: Tell us more, please. *Climatic Change,* **108,** 775–790, doi:10.1007/s10584-011-0187-5.

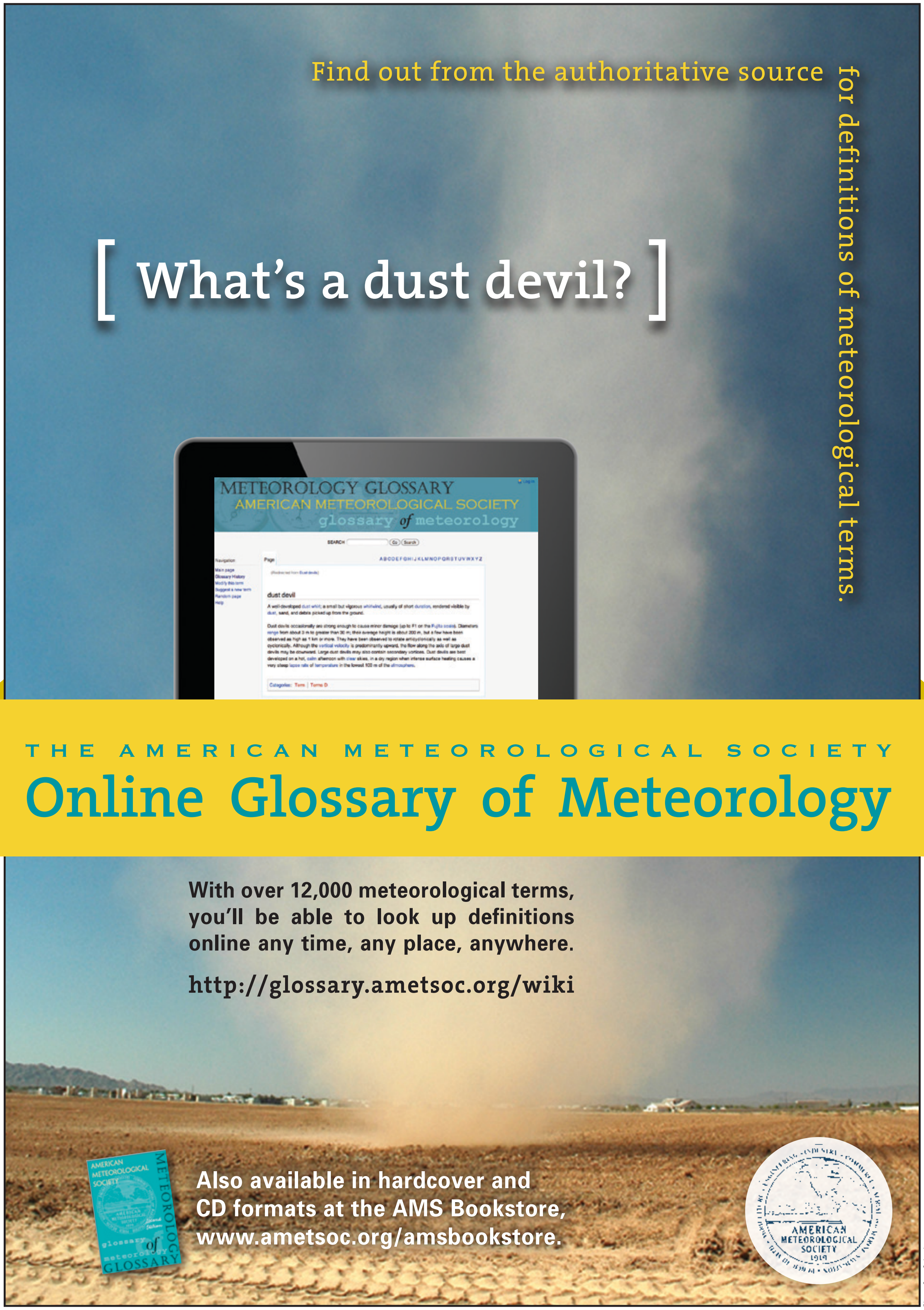
Solomon, S., R. Alley, J. Gregory, P. Lemke, and M. Manning, 2008: A closer look at the IPCC report. *Science,* **319,** 409–410, doi:10.1126/science.319.5862.409c.

Trenberth, K. E., 2005: Uncertainty in hurricanes and global warming. *Science,* **308,** 1753–1754, doi:10.1126/science.1112551.

——, 2011: Attribution of climate variations and trends to human influences and natural variability. *Wiley Interdiscip. Rev.: Climate Change,* **2,** 925–930, doi:10.1002/wcc.142.

Wynne, B., 1992: Uncertainty and environmental learning: Reconceiving science and policy in the preventive paradigm. *Global Environ. Change,* **2,** 111–127, doi:10.1016/0959-3780(92)90017-2.

Yohe, G., and M. Oppenheimer, 2011: Evaluation, characterization, and communication of uncertainty by the Intergovernmental Panel on Climate Change—An introductory essay. *Climatic Change,* **108,** 629–639, doi:10.1007/s10584-011-0176-8.



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CHANGING HOW EARTH SYSTEM MODELING IS DONE TO PROVIDE MORE USEFUL INFORMATION FOR DECISION MAKING, SCIENCE, AND SOCIETY

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A new mode of development for Earth system models is needed to enable better targeted and more informative projections for both decision makers and scientists.

The Earth system is the thin layer of the Earth that contains and supports life. It ultimately governs most processes vital to human health and wellbeing: from food and water availability to disease spread and global economics. It is the canonical example of a complex system, in which its dynamics, resulting from interacting multiscale and nonlinear processes, cannot be predicted from understanding any of its isolated components. Attempts to understand the Earth system and how it will change in the future therefore depend on computational models that represent, with varying levels of abstraction, physical, chemical, and biological components of the Earth system and their interactions (Randall et al. 2007; Edwards 2010).

Decades of research using such models have resulted in advances in the understanding of many Earth system processes, including the impacts of humans on climate. Models have also produced projections, combining current knowledge of the underlying science with a set of plausible future societal change scenarios to provide information to guide climate change mitigation policy. But what confidence can be assigned to the projections? Confidence about a particular climate projection is often judged by the agreement between different climate models, with greater confidence assigned to projected changes for which there is close agreement

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(Pachauri and Reisinger 2007), although other considerations, such as why the models disagree, are also taken into account. Agreements between climate models have predominantly occurred for physical phenomena occurring over large spatial scales. All models agree that the world will become warmer on average if CO_2 levels continue to increase (Stainforth et al. 2005; Pachauri and Reisinger 2007; Oreskes et al. 2010; Kerr 2011; Rowlands et al. 2012), and they all agree that the increases will be greater at higher latitudes (Pachauri and Reisinger 2007). However, they disagree in other aspects, such as by how much the world will warm (Oreskes et al. 2010; Bretherton et al. 2012), and these disagreements become more pronounced at finer, regional spatial scales (Pachauri and Reisinger 2007).

It is now widely recognized that differences in projections not only fail to recognize a variety of additional sources of uncertainty, but also inevitably become increasingly uncertain the further into the future they are extended. For instance, projections still rarely incorporate estimates of uncertainty in many model parameters and uncertainty arising from internal model variability, and so typically underestimate the uncertainty (Stainforth et al. 2007a,b; Brekke et al. 2008; Fischer et al. 2011; Bretherton et al. 2012). However, any model will also always imperfectly represent the dynamics of the real world by failing to account for all the factors determining the dynamics by deliberately not incorporating known processes and by obviously not accounting for unknown processes. Thus, projections will inevitably become less reliable, and thus uncertain, the further into the future they are extended (Smith 2002; Parker 2011; Smith and Stern 2011).

Despite their limitations, model projections are used by governments, businesses, and scientists to help make decisions. However, the lack of clarity about their uncertainty limits the extent to which they can be treated with any more sophistication than simply a collection of plausible outcomes (Cox and Stephenson 2007; Moss et al. 2010; Oreskes et al. 2010; Kerr 2011; Maslin and Austin 2012). For example, land use managers wishing to assess how precipitation might change in the future are typically confronted with a wide range of predictions about the direction and timing of change (Stainforth et al. 2007b; New et al. 2007; Stainforth 2010; Maslin and Austin 2012). Decision makers do not depend on consistent or confident projections in order to make decisions (Polasky et al. 2011; Kunreuther et al. 2013) but analyses of uncertainty and estimates of confidence in projections provide a much a clearer understanding of the need for, and likely consequences of, different decisions (Weaver et al. 2013; Lemos et al. 2012).

Of course, we do not suggest that Earth system modeling has not been useful in informing decision making. However, it has followed an approach that is better suited to exploring the plausible rather than identifying the probable. How can this situation be improved? How can we improve how model projections are made to provide clearer information to decision makers? We believe this can be facilitated by pursuing an alternative mode of model development; one that has the central aim of enabling the balance of models to be adjusted to allow balances of detail to be found that provide useful information for specific decisions.

DIFFERENT PERSPECTIVES ON THE FUTURE EVOLUTION OF MODELS. There is a diverse variety of models of the Earth system (Fig. 1) because the level of detail has evolved over time to address different scientific questions. The predominant direction of model development to date has been the addition of more details, simulating an increasing number of different processes. In so doing, they have increased our understanding of the Earth system. They have also evolved to simulate processes at increasingly finer spatial resolutions (Claussen et al. 2002; Randall et al. 2007; Slingo et al. 2009), enabling phenomena to be simulated that only begin to occur at finer spatial scales (such as hurricanes). However, it is important to recognize that the same advances have also brought costs that can reduce predictive accuracy (by "accuracy" we mean the degree to which model predictions are centered on the dynamics and states of real-world phenomena rather than, for example, the number of real-world processes that the models depict). We will detail these costs below but, as an example, efforts have been biased toward adding details to individual models that are already technically unwieldy and intractable (Held 2005), rather than enabling uncertainty in the different aspects to be assessed, quantified, and incorporated into predictions and projections ("predictions": estimates of how the Earth system will change; "projections": estimates of how the Earth system might change under different scenarios; Weaver et al. 2013).

Perspectives differ on how much time and resources should be spent on adding yet more details. One perspective is that this is likely to be worthwhile because the model projections, incorporating more processes and at finer spatial resolutions, will become more realistic (Slingo et al. 2009; Gent et al. 2009; Slingo 2010). However, this is true only if our understanding of those new processes, as expressed in model formulations and parameter values, is sufficient to enable the projections to reliably predict the dynamics of the system under future scenarios. For example, Oppenheimer et al. (2008) show that the continual refinement of model details can actually lead to "negative learning": where confidence improves over time to an answer that is different from the truth.

An alternative perspective is that continually adding details will unlikely deliver the desired improvements in decision-making capabilities (Dessai et al. 2009). Instead, it is proposed that the focus of making climate change decisions using projections should change from one that awaits sufficiently high confidence in what *will* happen before acting ("predict then act") to one that uses the projections as a set of plausible examples of what *might* happen to decide on how best to act in light of that knowledge and uncertainty (Stainforth et al. 2007b; Dessai et al. 2009; Kunreuther et al. 2013). Toward this goal, studies have investigated improving the process of decision making to make more robust decisions while incorporating information with different and diverse sources of uncertainty (Lempert and Collins 2007; Stakhiv 2011; Kunreuther et al. 2013; Weaver et al. 2013). These have led to the refinement of robust decision-making (RDM) methods within climate change decision making (Weaver et al. 2013). Existing model projections can already inform decision making under such frameworks, but for a limited range of scenarios and scales of spatial and temporal resolution. But they are not necessarily best suited for this purpose. To examine a range of scenarios, it would be more convenient to use models that could easily be simulated under many different scenarios (Weaver et al. 2013; Bretherton et al. 2012). Another focus has therefore been on how to redesign methodological frameworks for producing climate change projections so that they can be better targeted toward the needs of users (Weaver et al. 2013; Bretherton et al. 2012).

However, even if more robust decision-making frameworks are adopted, contemporary climate models still do not adequately convey important information that can be used to assess the confidence that can be placed in their projections. By "confidence" we mean an estimate of the probability of how the real-world system will behave. A related concept is the credibility of projections, which describes the assessment of a mechanistic model to reliably reproduce particular real-world phenomena (e.g., Brekke et al. 2008). Our perspective is that significant improvements to how climate models are developed are needed to provide more informative climate change projections. Such projections should go beyond being just a set of plausible outcomes to also convey a much more rigorous depiction of uncertainty in those projections than has been done to date. While any estimates of uncertainty will always become decreasingly reliable the further into the future they are projected (unless some proof can be given about the extent to which they truly bound real-world dynamics), they can still be seen as information-constrained predictions of the future, based on past evidence and understanding. Our focus here is on the methodological process of making the climate model projections themselves to better convey information and uncertainty relevant to the information being sought.

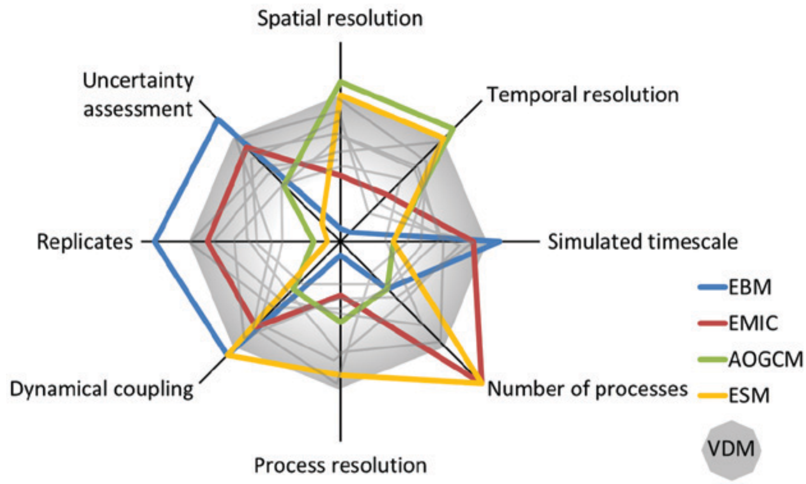

Fig. 1. Toward more balanced models of the Earth system. There currently exists a wide spectrum of models of the Earth system (Randall et al. 2007): Earth system models (ESMs), energy balance models (EBMs) (Lenton 2000), ESMs of intermediate complexity (EMICS) (Claussen et al. 2002), and atmosphere–ocean general circulation models (AOGCMs) (Murphy et al. 2004). Each prioritizes the allocation of computational resources (the area of the gray polygon) differently. Enabling and performing fluid navigation of this model space to identify a suitable balance of details will be a key part to our new approach, termed a variable detail model (VDM), here. Gray lines represent hypothetical alternative resource allocations in the VDM.

THE COSTS OF MODEL COMPLEXITY.

Contemporary practices are still limited in the extent to which they incorporate different sources of uncertainty into model projections. Uncertainty arises from multiple sources: from uncertainty in the data used to initialize, parameterize, and evaluate models; from uncertainty in how adequately models represent reality; from differences in our scientific understanding of processes and how to represent them in models; from uncertainty in whether the model has been implemented correctly; and from uncertainty arising from simulated random events occurring in real-world processes (Stainforth et al. 2007a; Masson and Knutti 2011; Slingo and Palmer 2011). Yet Earth system models are currently so computationally demanding that only between 3 and 10 simulations per scenario were recommended for decadal forecasts and hindcasts to inform the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Meehl and Bony 2011). This is a very low number of replicates to characterize a distribution in something so dynamically rich as global climate. For example, Deser et al. (2012; see Daron and Stainforth 2013 for another example) estimated how many simulations were needed to detect anthropogenic changes in air temperature, precipitation, and sea level pressure predicted by a general circulation model with its between-run variations arising only from simulated random atmospheric and oceanic processes. They found that <10 simulations were insufficient to detect changes in precipitation and sea level pressure for most regions of Earth, even over multidecadal time windows, with only changes in surface air temperature being reliably detected for most regions of Earth with such few replicates. Yet this is just for one model, not even a full Earth system model, under one scenario, using one major source of variation (internal variability), and for a few global properties. Awareness of the need to understand the degree of replication required to capture internal variability is increasing and it is notable that some modeling groups conducted many more than 10 simulations per scenario for their phase 5 of the Coupled Model Intercomparison Project (CMIP5) simulations (Stainforth et al. 2005; World Climate Research Programme 2013).

There have been significant efforts to incorporate parameter uncertainty into general circulation model projections to assess how it influences uncertainty (e.g., Murphy et al. 2004; Stainforth et al. 2005; Collins et al. 2006; Knight et al. 2007; Piani et al. 2007; Murphy et al. 2009; Fischer et al. 2011; Sanderson 2011; Rowlands et al. 2012; Sexton et al. 2012; Sexton and Murphy 2012). However, these have predominantly not been extended to other components of the Earth system (e.g., biological components), to full Earth system models, or to the functional forms assumed to represent particular Earth system processes (structural uncertainty; Slingo and Palmer 2011; Maslin and Austin 2012). Quantifying this additional uncertainty and reporting its consequences is being more commonly performed for components of Earth system models but it is yet unknown whether fully incorporating these, or the additional uncertainty of whether policy recommendations will be implemented when making future projections, will swamp any anticipated improvements in predictive precision from increasing the realism of existing components (Smith and Stern 2011; Palmer 2012).

It is also currently unknown how the partitioning of detail amongst model components influences the confidence that can be placed in predictions or projections (Smith 2002; Oreskes et al. 2010). For example, increasing the spatial resolution of a specific atmospheric physics model is justifiable in order to predict atmospheric dynamics more precisely (Shaffrey et al. 2009; Palmer 2012) but if its computational requirements restrict the inclusion of other details then the model may be less accurate than had an alternative atmospheric model formulation been adopted to allow other component processes to be represented more accurately. The adequacy of a model structure, including the level of detail, can be assessed by the degree to which predictions can recapture the known (and relevant) dynamics of interest, although such assessments are not in widespread use (Judd et al. 2008; Le Bauer et al. 2013; Smith et al. 2013).

It is also worth being aware that, fundamentally, more detailed models can make worse predictions than simpler models. This could occur, for example, if mechanisms or parameters are included as if they apply generally where they are in fact applicable to a much narrower range of circumstances. This is more likely to occur if models are tested against unchanging datasets because it raises the chances of a hypothetical mechanism being found that explains the variance in the specific dataset. This is known as overfitting, in which overly detailed models make worse predictions than simpler models through being overly tuned to the specifics of the calibration or training datasets (Bishop 2006; Crout et al. 2009; Masson and Knutti 2013).

Inadequate justification of the balance of details in models of the Earth system ultimately makes it difficult to meaningfully compare the projections of different models. Intercomparison exercises [such as the current Climate Model Intercomparison Project (Doblas-Reyes et al. 2011; Meehl and Bony 2011; Stouffer et al. 2011)] illustrate the degree of consistency between projections. However, the diverse and incompatible approaches to formulating and simulating models cause major difficulties in allowing detailed intercomparisons and the origins of differences in projections to be understood. The fact that some models used in intercomparisons are related, either by ancestry or by adoption of common formulations, means that the variation between their projections may be an overly conservative and biased estimate of the actual uncertainty (Stainforth et al. 2007a; Tebaldi and Knutti 2007; Dessai et al. 2009; Schwalm et al. 2009; Frank et al. 2010; Knutti et al. 2010; Smith and Stern 2011; Rowlands et al. 2012; Bishop and Abramowitz 2013). A rigorous analysis of the large ensemble from the general circulation model available at www.climateprediction.net reassuringly highlighted that variation due to hardware and software differences had relatively small effects on variation in model projections and that the effects arising from parameter variation were much larger (Knight et al. 2007). While extremely insightful, this analysis was performed for just one model structure and so it is largely unknown whether these findings apply more generally across a wider range of models.

A lack of detailed assessments of consistency of model components with historical observations, and the contributions of the uncertainties associated with model components to uncertainty in predictions, makes it unclear how best to proceed with future refinements. What are the most important and most reducible sources of uncertainty? Which components should be prioritized for refinement? What new data do we need to achieve this? Model development practices to date have insufficiently quantified the contributions of known sources of uncertainty to enable such questions to be addressed, although a number of model component intercomparison projects have been conducted, are planned, or are underway to help address some these issues, such as the Program for the Intercomparison of Land surface Parameterization Schemes (PILPS; Henderson-Sellers et al. 1996). Moreover, on top of the multiple necessary improvements to Earth system models, the research community will need to decide how best to make them in light of limited computational resources (Shukla et al. 2010; Palmer 2012).

AN ALTERNATIVE APPROACH. It is increasingly recognized that the current generation of model projections often do not provide decision makers, scientists, or climate model output users in general with the specific information they need (Corell et al. 2009; Dessai et al. 2009; Oreskes et al. 2010; Kerr 2011; Lemos et al. 2012; Lemos and Rood 2012; Maslin and Austin 2012; Kunreuther et al. 2013). For example, those making decisions in relation to future land use planning might wish to understand the diversity of risks (e.g., floods) posed to potential developments (e.g., flood barriers or wind farms) as a consequence of climate change (Weaver et al. 2013) but are confronted with a wide range of projections that differ in relevance, resolution, parent model, and uncertainty (to name a few) without clear information on their credibility or uncertainty. Recent advances in decision theory have gone a long way to enabling rational decisions in light of projected climate changes, irrespective of how models are developed (Polasky et al. 2011; Liverman et al. 2010; Kunreuther et al. 2013; Weaver et al. 2013). For example, instead of decision makers awaiting confident estimates of the likelihood of particular events happening in future before acting (e.g., the chances that storm surges in a particular port will exceed 5 m), decision theory now provides robust ways of estimating the costs and benefits of acting now given the range of costs associated with different plausible events (Weaver et al. 2013). However, given the costs arising from contemporary model development practices, it is also clear that a number of changes to those practices would not only enable projections to provide more useful information for decision makers, such as providing more complete estimates of uncertainty, but also better target the needs of a much wider community of climate model users (Liverman et al. 2010; Bretherton et al. 2012). We therefore recommend here changes to model development practices to better suit the needs of those aiming to make more informative climate projections. In Table 1 we summarize the differences between the approach we recommend and contemporary practices.

Given the costs of model complexity we think there should be a greater emphasis on adopting models that are at least simpler than the current generation of extremely computationally demanding Earth system models to permit more informative uncertainty quantification. Such quantification should be conducted to reflect the sensitivity of model projections to the most important known sources of uncertainty in relation to the phenomena being targeted for prediction. Such uncertainty assessments are becoming more common in relation to parameter uncertainty and internal variability and the results of these predominantly argue for many more replicates than typically conducted for the most complex models (Stainforth et al. 2005; Sanderson 2011; Rowlands et al. 2012; Sexton and Murphy 2012; Deser et al. 2012). However, uncertainty assessments also need to be extended to enable structural uncertainties to be assessed in more informative ways than is achieved to date through model intercomparisons. Ideally, structural uncertainty assessments would be part of the uncertainty quantification conducted by any one modeling team, incorporating the effects of alternative formulations for internal processes (e.g., alternative ways of representing vegetation fires) or even for entirely different formulations (e.g., comparing simpler models to more detailed models). Thus, when projections are served to users, they can be accompanied by a more rigorous exposition of the sensitivity of relevant model predictions to these different sources of uncertainty. However, such information should always be delivered with the caveat that any uncertainty or probability projection is increasingly likely to become misleading the further into the future it is projected.

Data assimilation and parameter inference methods will play key roles in future approaches to quantifying uncertainty in how the model reflects present day and historical phenomena. Such methods will be important for propagating uncertainty into projections and enabling assessments of the value of alternative model formulations in terms of precision, accuracy, and overall confidence in how well the model captures reality (Vrught et al. 2005; Berliner and Wikle 2007; Scholze et al. 2007; Sexton and Murphy 2012; Le Bauer et al. 2013; Smith et al. 2013). New studies examining the tradeoffs between the level of model detail and the ability to quantify uncertainty would be informative in relation to this (Smith 2002; Ferro et al. 2012; Palmer 2012). Formal probabilistic methods (i.e., Bayesian inference) are particularly well suited for comparing models with data and making projections that incorporate estimates of uncertainty, so would be particularly attractive for our proposed approach (Kass and Raftery 1995; Berger et al. 1999; Kennedy and O'Hagan 2001; Oakley and O'Hagan 2002; Berliner 2003). So far, these have proven computationally unfeasible for the most detailed models (Oreskes et al. 1994; Smith and Stern 2011; van Oijen et al. 2011; Palmer 2012), but this could be addressed on the short term in a number of ways. For instance, Bayesian emulators of detailed models could be employed to make probabilistic predictions based on limited runs of the computer code (Kennedy and O'Hagan 2001; Oakley and O'Hagan 2002), or the number of details could even be restricted to a level where their suitability could be assessed using Bayesian methods. However other, non-Bayesian methods to uncertainty quantification could also be used to provide useful information, such as the adjoint method—a popular choice for investigating the parameter sensitivity of computationally intensive models (Courtier et al. 1993).

Table 1. Contrasts between the traditional modes of model development and the approach we advocate here, summarizing the points made in the main text.

Current tendencies	Proposed changes
Oriented toward improving predictive precision of components independently	Focus improving components to increase overall confidence in model projections
Oriented toward precision of individual predictions over estimation of uncertainty	Bias toward accuracy of predictions, which requires uncertainty estimation
Detail incorporated because potentially important	All detail justified by relevance, empirical evidence, and accuracy metrics
Most detailed models used to make projections, with confidence assessment made using separate analyses	Focus on adopting the most informative overall balance of details, including measures of uncertainty
Most parameters and processes defined prior to model construction	Many more parameters and processes justified through data assimilation, with prior assumptions clearly stated and accessible
Lack of ability to assess distribution of uncertainty across model and identify where inconsistencies exist	Probabilistic accounting for model uncertainty and its propagation into predictions
Incompatibility between model versions and between models of different institutions	Emphasis on enabling interoperability of components to enable identification of suitable balance of details
Intercomparison more important than intercompatibility	Intercompatibility necessary for quantitative intercomparison
Better suited to scientific exploration of the plausible	Better suited to identification of the probable, with more thorough accounting for uncertainty

Climate models convey more confidence in projected phenomena when those phenomena arise in multiple different models and the reasons for them occurring are understood to be plausibly consistent with reality (Pachauri and Reisinger 2007; Held 2005). The classic example is the consistent prediction from all modes of abstraction—from simple physical principles to multiple complex climate models, that increasing greenhouse gas concentrations leads to a global warming response (of course neither guarantee this will actually occur in reality). New approaches to climate modeling to inform decision makers need improved ways to demonstrate the consistency of projections under the different sources of uncertainty described above, but also enable the reasons behind the occurrence of projected phenomena to be investigated, understood, and assessed for real-world relevance. Structuring the diversity of possible model details hierarchically is one way to facilitate this, which encouragingly was also the first recommendation of the National Academy of Sciences' "National Strategy for Advancing Climate Modelling" (Bretherton et al. 2012; "Evolve to a common national software infrastructure that supports a diverse hierarchy of different models for different purposes . . ."). The hierarchical organization of model details is particularly helpful for enabling the reasons for particular model predictions to be understood and then tested (Held 2005). Emergent phenomena can be studied at the simplest possible level and the reasons for their emergence investigated without having to also simulate and account for excessive detail. Thus, one of the most useful (and challenging) improvements that we recommend is to develop widely applicable hierarchical descriptions of Earth system processes to provide frameworks within which models of the Earth system can be formulated and characterized, both in terms of their structure and in terms of their predictions and projections (this was also recommended by Held 2005).

The balance of detail and sources of uncertainty considered relevant to a problem will obviously depend on the problem being addressed. For example, United Nations Framework Convention on Climate Change decision makers recommending global climate mitigation decisions may require models with a different balance of details (in terms of spatial resolution and numbers of processes) than water agencies aiming to plan new water supply and wastewater management systems for their region meet the demands of the next 25 years (Rogelj et al. 2013; Weaver et al. 2013). Thus, computational methods are also needed that facilitate the assessment and adjustment of the overall balance of model details relative to the questions posed, current knowledge, data, and uncertainty. Computational methods to enable the adjustment of details within the same modeling framework have already been developed for individual families of models to meet this requirement (e.g., the Met Office Unified Model; Pope et al. 2007), although these need to also be able to incorporate estimates of uncertainty in model components and parameters, so that the various costs and benefits of adopting different levels of abstraction discussed above can be assessed. These methods will also need to be extended to apply beyond an individual family of models, as described above, to allow the quantification and assessment of structural uncertainty. Adding to these challenges is the requirement (at least occasionally) to conduct assessments of the overall balance of details at a systemic level. This is for several reasons. First, because the different components are coupled through feedbacks, the coupling of different components might be necessary to assess the accuracy with which they can predict important emergent phenomena. Second, systemic assessments can enable the detection of logical inconsistencies between the predictions of different components. Third, systemic assessment can also help to avoid the development of details of any one area in such a way as to detrimentally affect the accuracy of the overall model or the assessment of its accuracy. Fourth, such assessments can be used to help identify the most important reducible sources of uncertainty. Such approaches are being developed for numerical weather prediction models, where the poorest performing model features can be identified (Judd et al. 2008).

Achieving the sort of "balanced complexity" modeling paradigm (Fig. 1) we advocate above will obviously be extremely challenging, for both sociological and technological reasons. Modeling groups adopt different methodological approaches and have differing incentives to adopt cross-institutional standards. Much model development to date is conducted in government-funded research institutions where there is typically an incentive structure for individuals and research teams to produce research findings within a period of months to years that is publishable in peer-reviewed journals. The high resource and technical requirements to build even one detailed Earth system model mean that individuals and groups are reluctant to undertake projects involving radical modifications to their modeling architectures because of the likely time and financial costs involved. However, just as the increasing recognition of the need to conduct model intercomparisons and benchmarking has promoted standards in compatibility data and model outputs we believe that the increasing need to utilize climate model information in decision-making context will promote methods that allow assessment of the costs and benefits of adopting different balances of detail for providing useful information.

So how could modeling systems be engineered to enable the methodological improvements described? One of the first steps will be to develop new, or evolve the existing, online repositories for model components, whole models, driver and assessment data, and model outputs (e.g., the Earth system grid; Williams et al. 2009). Such repositories should enable access to components independently from their original parent models so that other research groups can assess the implications of alternative formulations for that component. Similar assessments could be made in relation to the driver and assessment datasets as well as model structures. To facilitate the exchange of model components, future components could be developed in such a way that facilitates their use within alternative model structures. This strategy was recently employed by Smith et al. (2013) to develop a global terrestrial carbon model with the intention to facilitate investigations into the costs and benefits of alternative model components and formulations for predicting global terrestrial carbon. In that study the modeling framework included code libraries that enabled model components to obtain the data they require to make outputs from online databases, from local computers, or from other model components, depending on the structural information specified. This facilitated rapid experimentation with a wide variety of model structures.

Investigations into the effects of alternative model formulations will also benefit from adopting conventions for the description of models—their structures, components, and use histories (Dunlap et al. 2008). This should also help to minimize or eliminate reducible sources of uncertainty associated with the technical implementation of models. Uncertainty in model projections also exists because of differences in datasets, algorithms, methods, models, and simulation architectures used by different research groups. The importance of these specific details cannot practically be assessed among very different models (though see Knight et al. 2007). Thus, any new approach will benefit from enabling scientists anywhere to access pools of models and datasets and verify whether or not a change was an improvement (by various measures of performance).

The comparison of different model structures and component formulations could also be aided by the adoption of programming languages that make it easier for the intentions of the code to be understood. Functional modeling languages (Pedersen and Phillips 2009) allow for succinct and functional descriptions of models. This would not only aid in conveying the intended purpose of the code but would also aid the translation of the same underlying model to different coding languages (e.g., FORTRAN versus C++). This is one promising way of allowing interoperability between the components of models written by different institutions when it is inevitable that there would be some resistance to initiatives to adopt standards in model development. Enabling models to work with data, parameters, and predictions as probability distributions, just as naturally as they use with constants today, would also greatly facilitate modeling with uncertainty. Probabilistic programming languages are a relatively recent area of research and development aimed at facilitating the use of probability distributions and machine learning in general applications (Bishop 2013). Their application in Earth system modeling could simplify the process of computing with probability distributions. Recent developments in functional probabilistic programming languages could enable modelers to combine the benefits of both functional and probabilistic programming languages (Bhat et al. 2013). Enabling the continual quantification, storage, and retrieval of uncertainty associated with model components and projections will also require much larger computer memory requirements; this could be facilitated with online data storage and retrieval capabilities.

One of the benefits of adopting a hierarchical approach to defining the relationships amongst model components is that it should facilitate model reconstruction from simple representations to avoid becoming locked into one model or modeling approach. Ideally, model developers would be able to identify all top-level components currently known to be relevant to a particular set of phenomena (one of which, for example, might be the sea level in 100 years' time) and then, starting from the simplest possible representations of each of these, critically assess and reassess the adequacy of the level of detail used to model them. Further details, in terms of new model components (Fig. 1), would be added if justifiable. This approach to model development would not only lead to better predictions for less computing time, but also tend to check the sociological imbalances inherent to current Earth system science, helping to direct intellectual effort and scientific funding toward those components that are the *least* understood and most useful in relation to the phenomena being targeted for prediction.

Any new modeling approach to get informative projections to users on demand and operate within formal or informal decision-making frameworks will also require the ability for researchers to specify, combine, and compare projections from multiple models—some perhaps projecting on demand and others obtained from archives to suit their analyses (Bretherton et al. 2012; Weaver et al. 2013). Such systems should be designed to allow a much broader community of experts to contribute to model development and use, including some that have had little influence on model development to date. It should also permit the coproduction of new climate information from climate modelers, domain experts, and decision makers—to enable a balance to be struck between providing the information that decision makers want and the information that scientists think decision makers need to know (Lemos and Rood 2012).

CONCLUSIONS. It is now time to build from the wealth of modes of abstraction of the Earth system developed so far, on the wealth of data in existence, and on advances in computation and statistics to build climate models that deliver much more predictive information for users. A key step toward this is to enable models to be built that include much more robust estimates of uncertainty, which in turn guides where scientific and computational resources need to be directed in order to reduce uncertainties further. Combining adaptive hierarchical modeling frameworks with assessments of the uncertainty in model formulations and projections will enable much better targeted explorations of model-detail space and allow urgent questions to be answered in a much more timely and reliable way.

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REFERENCES

Berger, J. O., B. Liseo, and R. L. Wolpert, 1999: Integrated likelihood methods for eliminating nuisance parameters. *Stat. Sci.,* **14,** 1–28, doi:10.1214/ss/1009211804.

Berliner, M. L., 2003: Uncertainty and climate change. *Stat. Sci.,* **18,** 411–533, doi:10.1214/ss/1081443227.

——, and C. K. Wikle, 2007: A Bayesian tutorial for data assimilation. *Physica D,* **230,** 1–16, doi:10.1016/j.physd.2006.09.017.

Bhat, S., J. Borgstroem, A. D. Gordon, and C. Russo, 2013: Deriving probability density functions from probabilistic functional programs. *Tools and Algorithms for the Construction and Analysis of Systems,* N. Piterman and S. Smolka, Eds., Lecture Notes in Computer Science, Vol. 7795, Springer, 508–522.

Bishop, C. H., and G. Abramowitz, 2013: Climate model dependence and the replicate Earth paradigm. *Climate Dyn.,* **41,** 885–900, doi:10.1007/s00382-012-1610-y.

Bishop, C. M., 2006: *Pattern Recognition and Machine Learning.* Springer, 738 pp.

——, 2013: Model-based machine learning. *Philos. Trans. Roy. Soc. London,* **A371,** 1–17, doi:10.1098/rsta.2012.0222.

Brekke, L. D., M. D. Dettinger, E. P. Maurer, and M. Anderson, 2008: Significance of model credibility in estimating climate projection distributions for regional hydroclimatological risk assessments. *Climatic Change,* **89,** 371–394, doi:10.1007/s10584-007-9388-3.

Bretherton, C., and Coauthors, 2012: *A National Strategy for Advancing Climate Modeling.* The National Academies Press, 294 pp.

Claussen, M., and Coauthors, 2002: Earth system models of intermediate complexity: Closing the gap in the spectrum of climate system models. *Climate Dyn.,* **18,** 579–586, doi:10.1007/s00382-001-0200-1.

Collins, M., B. B. B. Booth, G. R. Harris, J. M. Murphy, D. M. H. Sexton, and M. J. Webb, 2006: Towards quantifying uncertainty in transient climate change. *Climate Dyn.,* **27,** 127–147, doi:10.1007/s00382-006-0121-0.

Corell, R. W., and Coauthors, 2009: *Informing Decisions in a Changing Climate.* National Academies Press, 200 pp.

Courtier, P., J. Derber, R. Errico, J. Loiuis, and T. Vukicevic, 1993: Important literature on the use of adjoint, variational methods and the Kalman filter in meteorology. *Tellus,* **45,** 342–357, doi:10.1034/j.1600-0870.1993.t01-4-00002.x.

Cox, P., and D. A. Stephenson, 2007: Changing climate for prediction. *Science,* **317,** 207–208, doi:10.1126/science.1145956.

Crout, N. M. J., D. Tarsitano, and A. T. Wood, 2009: Is my model too complex? Evaluating model formulation using model reduction. *Environ. Modell. Software,* **24,** 1–7, doi:10.1016/j.envsoft.2008.06.004.

Daron, J. D., and D. A. Stainforth, 2013: On predicting climate under climate change. *Environ. Res. Lett.,* **8,** 034021, doi:10.1088/1748-9326/8/3/034021.

Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2012: Uncertainty in climate change projections: The role

of internal variability. *Climate Dyn.,* **38,** 527–546, doi:10.1007/s00382-010-0977-x.
Dessai, S., M. Hulme, R. Lampert, and R. Pielke Jr., 2009: Do we need better predictions to adapt to a changing climate? *Eos, Trans. Amer. Geophys. Union,* **90,** 111–112, doi:10.1029/2009EO130003.
Doblas-Reyes, F. J., G. J. van Oldernborgh, J. Garcia-Serrano, H. Pohlmann, A. A. Scaife, and D. Smith, 2011: CMIP5 near-term climate prediction. *CLIVAR Exchanges,* No. 56, International CLIVAR Project Office, Southampton, United Kingdom, 8–11.
Dunlap, R., and Coauthors, 2008: Earth system curator: Metadata infrastructure for climate modelling. *Earth Sci. Inf.,* **1,** 131–149, doi:10.1007/s12145-008-0016-1.
Edwards, P. N., 2010: *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming.* MIT Press, 552 pp.
Ferro, C. A. T., T. E. Jupp, F. H. Lambert, C. Huntingford, and P. M. Cox, 2012: Model complexity versus ensemble size: Allocating resources for climate prediction. *Philos. Trans. Roy. Soc. London,* **A370,** 1087–1099, doi:10.1098/rsta.2011.0307.
Fischer, E. M., D. M. Lawrence, and B. M. Sanderson, 2011: Quantifying uncertainties in projections of extremes—A perturbed land surface parameter experiment. *Climate Dyn.,* **37,** 1381–1398, doi:10.1007/s00382-010-0915-y.
Frank, D. C., J. Esper, C. C. Raible, U. Büntgen, V. Trouet, B. Stocker, and F. Joos, 2010: Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. *Nature,* **463,** 527–530, doi:10.1038/nature08769.
Gent, P., and Coauthors, 2009: Community Earth System Model science plan: 2009–2015. CESM Scientific Steering Committee, 31 pp.
Held, I. M., 2005: The gap between simulation and understanding in climate modeling. *Bull. Amer. Meteor. Soc.,* **86,** 1609–1614, doi:10.1175/BAMS-86-11-1609.
Henderson-Sellers, A., K. McGuffie, and A. J. Pitman, 1996: The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS): 1992 to 1995. *Climate Dyn.,* **12,** 849–859, doi:10.1007/s003820050147.
Judd, K., C. A. Reynolds, T. E. Rosmond, and L. A. Smith, 2008: The geometry of model error. *J. Atmos. Sci.,* **65,** 1749–1772, doi:10.1175/2007JAS2327.1.
Kass, R. E., and A. E. Raftery, 1995: Bayes factors. *J. Amer. Stat. Soc.,* **90,** 773–795, doi:10.1080/01621459.1995.10476572.
Kennedy, M. C., and A. O'Hagan, 2001: Bayesian calibration of computer models (with discussion). *J. Roy. Stat. Soc.,* **63B,** 425–464, doi:10.1111/1467-9868.00294.
Kerr, R. A., 2011: Time to adapt to a warming world, but where's the science? *Science,* **334,** 1052–1053, doi:10.1126/science.334.6059.1052.
Knight, C. G., and Coauthors, 2007: Association of parameter, software, and hardware variation with large-scale behavior across 57,000 climate models. *Proc. Nat. Acad USA,* **104,** 12 259–12 264, doi:10.1073/pnas.0608144104.
Knutti, R., R. Furrer, J. Cermak, and G. A. Meehl, 2010: Challenges in combining projections from multiple climate models. *J. Climate,* **23,** 2739–2758, doi:10.1175/2009JCLI3361.1.
Kunreuther, H., G. Heal, M. Allen, O. Edenhofer, C. B. Field, and G. Yohe, 2013: Risk management and climate change. *Nat. Climate Change,* **3,** 447–450, doi:10.1038/nclimate1740.
Le Bauer, D. S., D. Wang, K. T. Richter, C. C. Davidson, and M. C. Dietze, 2013: Facilitating feedbacks between field measurements and ecosystem models. *Ecol. Monogr.,* **83** (2), 133–154, doi:10.1890/12-0137.1.
Lemos, M. C., and R. B. Rood, 2012: Climate projections and their impact on policy and practice. *Wiley Interdiscip. Rev.: Climatic Change,* **1,** 670–682.
——, C. J. Kirchhoff, and V. Ramprasad, 2012: Narrowing the climate information usability gap. *Nat. Climate Change,* **2,** 789–794, doi:10.1038/nclimate1614.
Lempert, R. J., and M. T. Collins, 2007: Managing the risk of uncertain threshold responses: Comparison of robust, optimum, and precautionary approaches. *Risk Anal.,* **27,** 1009–1026, doi:10.1111/j.1539-6924.2007.00940.x.
Lenton, T. M., 2000: Land and ocean carbon cycle feedback effects on global warming in a simple Earth system model. *Tellus,* **52,** 1159–1188, doi:10.1034/j.1600-0889.2000.01104.x.
Liverman, D., and Coauthors, 2010: *Informing an Effective Response to Climate Change.* The National Academies Press, 348 pp.
Maslin, M., and P. Austin, 2012: Climate models at their limit? *Nature,* **486,** 183–184, doi:10.1038/486183a.
Masson, D., and R. Knutti, 2011: Climate model genealogy. *Geophys. Res. Lett.,* **38,** L08703, doi:10.1029/2011GL046864.
——, and ——, 2013: Predictor screening, calibration, and observational constraints in climate model ensembles: An illustration using climate sensitivity. *J. Climate,* **26,** 887–898, doi:10.1175/JCLI-D-11-00540.1.
Meehl, G. A., and S. Bony, 2011: Introduction to CMIP5. *CLIVAR Exchanges,* No. 56, International CLIVAR Project Office, Southampton, United Kingdom, 4–5.
Moss, R. H., and Coauthors, 2010: The next generation of scenarios for climate change research

and assessment. *Nature,* **463,** 747–756, doi:10.1038/nature08823.

Murphy, J. M., D. M. H. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, M. Collins, and D. A. Stainforth, 2004: Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature,* **430,** 768–772, doi:10.1038/nature02771.

——, and Coauthors, 2009: UK Climate Projections science report: Climate change projections. Met Office Rep., 10 pp.

New, M., A. Lopez, S. Dessai, and R. Wilby, 2007: Challenges in using probabilistic climate change information for impact assessments: An example from the water sector. *Philos. Trans. Roy. Soc. London,* **A365,** 2117–2131, doi:10.1098/rsta.2007.2080.

Oakley, J. E., and A. O'Hagan, 2002: Bayesian inference for the uncertainty distribution of computer model outputs. *Biometrika,* **89,** 769–784, doi:10.1093/biomet/89.4.769.

Oppenheimer, M., B. C. O'Neill, and M. Webster, 2008: Negative learning. *Climatic Change,* **89,** 155–172, doi:10.1007/s10584-008-9405-1.

Oreskes, N., K. Schrader-Frechette, and K. Belitz, 1994: Verification, validation, and confirmation of numerical models in the earth sciences. *Science,* **263,** 641–646, doi:10.1126/science.263.5147.641.

——, D. A. Stainforth, and L. A. Smith, 2010: Adaptation to global warming: Do climate models tell us what we need to know? *Philos. Sci.,* **77,** 1012–1028, doi:10.1086/657428.

Pachauri, R. K., and A. Reisinger, Eds., 2007: Climate Change 2007: Synthesis report. IPCC Rep., 73 pp.

Palmer, T. N., 2012: Towards the probabilistic Earth-system simulator: A vision for the future of climate and weather prediction. *Quart. J. Roy. Meteor. Soc.,* **138,** 841–861, doi:10.1002/qj.1923.

Parker, W. S., 2011: When climate models agree: The significance of robust model predictions. *Philos. Sci.,* **78,** 579–600, doi:10.1086/661566.

Pedersen, M., and A. Phillips, 2009: Towards programming languages for genetic engineering of living cells. *J. Roy. Soc. Interface,* **6,** S437–S450, doi:10.1098/rsif.2008.0516.focus.

Piani, C., B. Sanderson, F. Giorgi, D. J. Frame, C. Christensen, and M. R. Allen, 2007: Regional probabilistic climate forecasts from a multithousand, multimodel ensemble of simulations. *J. Geophys. Res.,* **112,** D24108, doi:10.1029/2007JD008712.

Polasky, S., S. R. Carpenter, C. Folke, and B. Keeler, 2011: Decision-making under great uncertainty: Environmental management in an era of global change. *Trends Ecol. Evol.,* **26,** 398–404, doi:10.1016/j.tree.2011.04.007.

Pope, V., and Coauthors, 2007: The Met Office Hadley Centre climate modelling capability: The competing requirements for improved resolution, complexity and dealing with uncertainty. *Philos. Trans. Roy. Soc. London,* **A365,** 2635–2657, doi:10.1098/rsta.2007.2087.

Randall, D. A., and Coauthors, 2007: Climate models and their evaluation. *Climate Change 2007: The Physical Science Basis,* S. Solomon et al., Eds., Cambridge University Press, 589–662.

Rogelj, J., D. L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013: Probabilistic cost estimates for climate change mitigation. *Nature,* **493,** 79–83, doi:10.1038/nature11787.

Rowlands, D. J., and Coauthors, 2012: Broad range of 2050 warming from an observationally constrained large climate model ensemble. *Nat. Geosci.,* **5,** 256–260, doi:10.1038/ngeo1430.

Sanderson, B. M., 2011: A multimodel study of parametric uncertainty in predictions of climate response to rising greenhouse gas concentrations. *J. Climate,* **24,** 1362–1377, doi:10.1175/2010JCLI3498.1.

Scholze, M., T. Kaminski, P. Rayner, W. Knorr, and R. Giering, 2007: Propagating uncertainty through prognostic carbon cycle data assimilation system simulations. *J. Geophys. Res.,* **112,** D17305, doi:10.1029/2007JD008642.

Schwalm, C. R., and Coauthors, 2009: A model-data intercomparison of CO_2 exchange across North America: Results from the North American Carbon Program site synthesis. *J. Geophys. Res.,* **115,** G00H05, doi:10.1029/2009JG001229.

Sexton, D. M. H., and J. M. Murphy, 2012: Multivariate probabilistic projections using imperfect climate models. Part II: Robustness of methodological choices and consequences for climate sensitivity. *Climate Dyn.,* **38,** 2543–2558, doi:10.1007/s00382-011-1209-8.

——, ——, M. Collins, and M. J. Webb, 2012: Multivariate probabilistic projections using imperfect climate models part I: Outline of methodology. *Climate Dyn.,* **38,** 2513–2542, doi:10.1007/s00382-011-1208-9.

Shaffrey, L. C., and Coauthors, 2009: U.K. HiGEM: The New U.K. High-Resolution Global Environment Model—Model description and basic evaluation. *J. Climate,* **22,** 1861–1896, doi:10.1175/2008JCLI2508.1.

Shukla, J., and Coauthors, 2010: Toward a new generation of world climate research and computing facilities. *Bull. Amer. Meteor. Soc.,* **91,** 1407–1412, doi:10.1175/2010BAMS2900.1.

Slingo, J., 2010: Met Office science strategy (2010–2015). Met Office, 15 pp.

——, and T. Palmer, 2011: Uncertainty in weather and climate prediction. *Philos. Trans. Roy. Soc. London,* **A369,** 4751–4767, doi:10.1098/rsta.2011.0161.

——, and Coauthors, 2009: Developing the next-generation climate system models: Challenges and achievements. *Philos. Trans. Roy. Soc. London,* **A367,** 815–831, doi:10.1098/rsta.2008.0207.

Smith, L. A., 2002: What might we learn from climate forecasts? *Proc. Natl. Acad. Sci. USA,* **99,** 2487–2492, doi:10.1073/pnas.012580599.

——, and N. Stern, 2011: Uncertainty in science and its role in climate policy. *Philos. Trans. Roy. Soc. London,* **A369,** 4818–4841.

Smith, M. J., D. W. Purves, M. C. Vanderwel, V. Lyutsarev, and S. Emmott, 2013: The climate dependence of the terrestrial carbon cycle, including parameter and structural uncertainties. *Biogeosciences,* **10,** 583–606, doi:10.5194/bg-10-583-2013.

Stainforth, D., 2010: Estimating uncertainty in future climate projections. Workshop on nonstationarity, hydrologic frequency analysis, and water management, J. R. Olsen, J. Kiang, and R. Waskom, Eds., Colorado Water Institute Information Series 109, 175–182.

——, and Coauthors, 2005: Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature,* **433,** 403–406, doi:10.1038/nature03301.

——, M. R. Allen, E. R. Tredger, and L. A. Smith, 2007a: Confidence, uncertainty and decision-support relevance in climate predictions. *Philos. Trans. Roy. Soc. London,* **A365,** 2145–2161, doi:10.1098/rsta.2007.2074.

——, T. E. Downing, R. Washington, A. Lopez, and M. New, 2007b: Issues in the interpretation of climate model ensembles to inform decisions. *Philos. Trans. Roy. Soc. London,* **A365,** 2163–2177, doi:10.1098/rsta.2007.2073.

Stakhiv, E. Z., 2011: Pragmatic approaches for water management under climate change uncertainty. *J. Amer. Water. Res. Assoc.,* **47,** 1183–1196, doi:10.1111/j.1752-1688.2011.00589.x.

Stouffer, R. J., K. E. Taylor, and G. A. Meehl, 2011: CMIP5 long-term experimental design. *CLIVAR Exchanges,* No. 56, International CLIVAR Project Office, Southampton, United Kingdom, 5–7.

Tebaldi, C., and R. Knutti, 2007: The use of the multi-model ensemble in probabilistic climate projections. *Philos. Trans. Roy. Soc. London,* **A365,** 2053–2075, doi:10.1098/rsta.2007.2076.

van Oijen, M., and Coauthors, 2011: A Bayesian framework for model calibration, comparison and analysis: Application to four models for the biogeochemistry of a Norway spruce forest. *Agric. For. Meteor.,* **151,** 1609–1621, doi:10.1016/j.agrformet.2011.06.017.

Vrught, J. A., C. G. H. Diks, H. V. Gupta, W. Bouten, and J. M. Verstraten, 2005: Improved treatment of uncertainty in hydrologic modeling: Combining the strengths of global optimization and data assimilation. *Water Resour. Res.,* **41,** W01017, doi:10.1029/2004WR003059.

Weaver, C. P., R. J. Lempert, C. Brown, J. A. Hall, D. Revell, and D. Sarewitz, 2013: Improving the contribution of climate model information to decision making: The value and demands of robust decision frameworks. *Wiley Interdiscip. Rev.: Climate Change,* **4,** 39–60.

Williams, D. N., and Coauthors, 2009: The Earth System Grid: Enabling access to multimodel climate simulation data. *Bull. Amer. Meteor. Soc.,* **90,** 195–205, doi:10.1175/2008BAMS2459.1.

World Climate Research Programme, cited 2013: CMIP5 - data access - data portal. [Available online at http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html.]

NEW DIRECTIONS FOR THE AMS SYMPOSIUM ON EDUCATION

BY DONNA J. CHARLEVOIX, RAJUL PANDYA, ALISON BRIDGER, THOMAS E. GILL, ELAINE HAMPTON, REDINA HERMAN, JOHN KNOX, WEN-WHAI LI, AND DIANE STANITSKI

The 2013 American Meteorological Society (AMS) Symposium on Education continued its tradition of bringing together educators, researchers, professionals, and students to share innovations in education and increase the understanding of the role of educational activities and practices to benefit all ages of learners. The 2-day symposium included 32 oral presentations and 56 posters (available at online at https://ams.confex.com/ams/93Annual/webprogram/22EDUCATION.html).

Instruction and learning have moved well beyond presentations and lecturing and the organizing committee of the symposium aimed to model best practice in the structure of several sessions. This symposium was groundbreaking in that it included two nontraditional session formats: a panel discussion of award-winning instructors and an interactive format for sharing innovations in university and professional development; both sessions were evaluated.

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THE AMS TWENTY-SECOND SYMPOSIUM ON EDUCATION

WHAT: AMS Annual Meeting attendees from all professional avenues met to share innovations in teaching, best practices, and program highlights that advance education initiatives and learning of the atmospheric and related sciences, including the demonstration of best practices within a nontraditional session format and the integration of multiple stakeholders and learners for program success.
WHEN: 5–10 January 2013
WHERE: Austin, Texas

The symposium also built on the recent direction of highlighting interdisciplinary, multiple stakeholder work around societally relevant themes, one such example is shared here.

Attendees to the symposium and other Annual Meeting attendees interested in advancing education issues in the atmospheric and related sciences participated in an Education Symposium Discussion at the conclusion of the symposium. The goal of the open discussion was to begin a dialog to inform future directions of both the Symposium on Education and the development of a broader AMS education community.

THEME 1: DEMONSTRATION OF BEST PRACTICES WITH NONTRADITIONAL SESSION FORMAT. *Panel of teaching award winners.* Delivery of content via lecture format or as a presentation is typically less effective and conducive to learning than more interactive formats.

The symposium took the first steps in challenging the typical meeting presentation method with a panel discussion of the previous Teaching Excellence Award (TEA; now the Edward N. Lorenz Teaching Excellence Award) winners. The Teaching Excellence Award is given annually to an individual in recognition of sustained outstanding teaching and mentoring at the undergraduate and/or graduate levels in the atmospheric, oceanic, and related sciences. The panel session Creative and Effective Teaching in Challenging Times highlighted the talents and teaching experiences of recent TEA winners. Panel members included Steven Ackerman, University of Wisconsin–Madison (2009); Henry Fuelberg, Florida State University (2011); Robert Fovell, University of California, Los Angeles (2012); and Bruce Albrecht, University of Miami (2013). Each panelist provided a 15- to 20-min presentation in the style they typically use to teach classes. Each panelist provided a description and demonstration of their own innovative and interactive teaching methods, followed by a discussion about their teaching philosophy and style.

The panel session was very well received, with over 100 people in attendance—everyone from students to AMS fellows. Results of an audience survey show that that they agreed or strongly agreed that the format of this session was more beneficial than a traditional oral presentation to learn about effective teaching. Participants indicated they would like to see this format used again in future symposiums. Attendees of the panel discussion suggested longer, more interactive demonstrations of teaching styles that are presented on an elevated stage in the room, along with the possibility of a panelwide debate discussing unique styles of teaching.

Interactive sessions. Building on the alternative presentation format of the panel discussion, the University and Professional Education Initiatives sessions offered a more interactive session format with a goal of providing a smaller, more intimate setting where presenters could interact with attendees. Five speakers presented innovative approaches to education through active participation by the audience. Presentation talks ranged from the impact of department social structure on teaching practices and community-based fieldwork for undergraduate research to comparative assessment of student learning with varied instructional deliveries to inform best practice.

The second interactive session consisted of four roundtable presentations that required a physical transformation of the room setup. Tables were placed in each corner with 20 to 25 chairs available for attendees to meet with the presenter at each table. Presenters conveyed their work via 10-min demonstrations with a short question-and-answer period after. Audience members rotated through the different demonstrations. Presenters demonstrated techniques to enhance problem solving, showed ways to use data in the classroom to facilitate undergraduate research, highlighted online resources for the instruction of tropical synoptic meteorology, and demonstrated instrumentation used to teach observation and data collection fundamentals. All of these sessions included one-on-one interaction between the presenter and the audience, as well as lively discussions that would not have been possible in the usual presentation format. The session was well attended with 65 to 90 participants at any given time during the session.

Evaluation analysis found that the format was well received. Attendees found the more intimate setting and the interaction between audience and speaker preferable to the traditional meeting lecture format. Improvements for similar future sessions will include more guidance to presenters to ensure the focus is on interaction with attendees. The most significant challenge for the four concurrent interactive sessions was the physical setup of the room. Traditional conference room setup is not conducive to one-on-one interaction with the speaker, and the size of the room that is ideal for a traditional presentation is too small to break into multiple interactive groups. Sufficient lead time and planning is critical to coordinate the changes to the physical layout of the room with both the AMS staff and conference hall facility. These logistical issues are well worth overcoming to allow the level of interaction and "group thinking" that took place in the University and Professional Education Initiatives sessions.

THEME 2: EDUCATIONAL BENEFITS FROM MULTIPLE STAKEHOLDERS. Instructional programs focused on complex topics, such as climate change and air pollution, are becoming more common in that they provide learners with multiple aspects of information and typically bring together multiple people with varying expertise. The depth and breadth of such programs is proving to be an effective way to reach students at multiple levels. Elaine Hampton and Tom Gill of The University of Texas at El Paso (UTEP) shared their program (Buen Ambiente-Buena Salud) experience that links UTEP with the U.S. Environmental Protection Agency (EPA), El Paso Independent School District (EPISD), and the North American Association for Environmental Education's (NAAEE) Guidelines for Excellence.

The program is supported by the EPA and is designed to train UTEP students in air pollution science and engineering and then to place and provide financial support to them in summer air quality–related internships with a variety of agencies and corporations. The objective of the UTEP–EPA air quality internship and training program is to increase the number of future air quality professionals in the U.S.–Mexico border region by recruiting students and providing them with training, education, civic engagement, and internship opportunities in air quality–related fields.

In parallel, through a strong partnership with EPISD, curriculum lead writers and master science teachers at UTEP are creating curriculum modules that address local and regional air quality. Each year, all students in third grade through high school will experience at least one module of inquiry learning experiences about air pollution. Each unit aligns with state standards and addresses NAAEE's Guidelines for Excellence to ensure that the students are engaged in inquiry learning with activities that lead to community or civic action. This is a unique curriculum modification in that environmental education, often ignored or addressed only slightly in enrichment lessons, will be formalized and institutionalized into the district's full curriculum. Because El Paso is a bilingual community, activities are designed to enhance learning for English language learners.

The program draws on the social, economic, scientific, and political context of the community so that the students see the relevance to their border environment and the social justice context. By the 2014/15 school year, the curriculum will reach approximately 50,000 students each year—predominantly Hispanic students from communities whose members have been underrepresented in science, technology, engineering, and mathematics (STEM) careers.

Building the education community. The symposium concluded with an inclusive conversation about the Education Symposium. The goal was to seek ideas to make the symposium even more dynamic, to better connect it to research and other research-focused symposia, and to interest more Annual Meeting attendees in participating. Over 50 attendees provided feedback on the innovative sessions of the symposium, volunteered to serve on the symposium planning committee and other activities, and provided guidance and input to shape the 2014 Symposium on Education. All Society members are encouraged to help build the AMS education community through the Symposium on Education or any of the many education-focused activities the AMS supports.

45 BEACON

LETTER FROM HEADQUARTERS

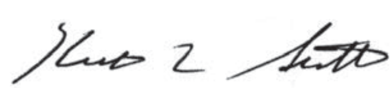
THE QUESTIONS KIDS ASK— ARE YOU UP TO THE CHALLENGE?

When I was a kid, I would spend hours in my back yard watching the clouds. I would not be trying to find the shapes of dinosaurs, rabbits, or fish the way some of my friends did, but instead I tried to visualize the three-dimensional air currents that must exist to create what I saw. Some days I could witness the full life cycle of a small cumulus cloud, from an almost imperceptible irregularity in an otherwise uniformly hazy region of the sky, to a growing visible cloud, to the final few patchy remnants disappearing as the cloud evaporated, with the whole cycle happening over the span of just a dozen or so minutes. At the time, I wondered about why that cloud formed where it did, and what determined why it did not grow larger or last longer—especially when there were larger long-lived cumulus clouds in other parts of the sky.

Years later, as I learned more about the dynamics of the atmosphere, I gained a much deeper appreciation for the complexity of the motion field associated with even so benign a weather situation as a field of fair-weather cumulus on a summer afternoon. Indeed, with that much deeper understanding of the way the atmosphere works, those questions that I asked as a kid are perhaps even more fascinating to ponder as one looks at the sky: Why did that cloud form exactly where it did? Why was its life cycle different from its neighbors?

With the start of another academic year, I look forward to the chance to visit classrooms in some of the elementary and middle schools in the Boston area to talk about weather and climate. I find that these students routinely ask questions about the weather that are much more sophisticated than they can possibly realize—just as I did, when I was a kid looking up at clouds. Providing scientifically sound answers appropriate to their level of education can be challenging, to be sure, but also really enjoyable. While these classroom visits offer me a chance to share my passion for science with the students—and hopefully fuel the excitement they may already have for science—I find that the interactions energize me in ways that make me feel I probably get more value from the visit than the students do!

Last month in this column, I described AMS initiatives to improve STEM education across the nation, and noted that all AMS members can take pride in those significant and measurably successful efforts. This month, I am hoping to encourage at least some of you reading this to join other members who help improve STEM education one classroom visit at a time. If you contact a local school and offer to come in for a classroom visit to talk about your science, you are likely to have your offer enthusiastically accepted. Work with the teacher of the class before your visit to help ensure that you are well prepared and that you cover materials that fit their level and curriculum. I can assure you that your efforts will result in a rewarding experience for the students and for you as well.



KEITH L. SEITTER, CCM
EXECUTIVE DIRECTOR

A series of profiles celebrating AMS Certified Broadcast Meteorologists and Sealholders

10 Questions with James Castillo

Meteorologist, KTLA, Los Angeles, California

What inspired you to go into broadcasting? I grew up in the Midwest, the heartland, outside of St. Louis. We always had the most amazing thunderstorms and some wicked tornadoes, not to mention the heat waves, the ice storms, snowstorms—even blizzards, river flooding, street flooding, high-wind events, and earthquakes. I wanted to know how and why these things happened and I wanted to share the information with the world.

When did you know you wanted to become a meteorologist/broadcaster? It was April 1980 when an F3 tornado hit my neighborhood outside of St. Louis. Now they're called EF3 tornadoes. Lucky for my family, it was beginning to lift as it was going right over our house, but the trees bent to the ground and I will never forget the power flashes mixed with the lightning. Checking on the neighbors also sticks in my memory.

How do you evaluate success? I evaluate success by looking at the news and weather team and seeing all the different things we add to the team. I always see a station as being a team. Everyone in front of the camera and behind the scenes should come together and accept all of the unique differences and be able to see that each and every player is the true reason the station is successful or not.

What do you think the next "big thing" is in weather reporting? I think the next big thing in weather reporting may be that graphics systems continue to be viewer friendly, easy to follow, yet full of great knowledge. In every television market I've been in, weather and breaking news are the big winners in the ratings. That has never changed.

What is the best thing about what you do? The best thing about doing television news/weather is getting to know the people in the market. Seeing all of the different types of people is very exciting and so interesting. I've enjoyed seeing America over the years and the different people and cities that make up this great country.

How would you define the value of the AMS certification programs? With my degree in atmospheric science and my AMS Seal, I used to think the CBM was not as important. Well, I changed my mind last year and got my CBM. I'm very proud to say the studying was fun and a wonderful refresher. This is what we all need. Studying for the CBM got me motivated again and updated.

How do you deal with criticism over forecasts that don't pan out? Usually, I find that the forecasts are very accurate. If we do have a "miss" you have to own it and move on. I always say, don't get angry if the forecast isn't exactly as you planned, because most of the time it really is accurate, and you know the wonderful people in your viewing area will support you.

What weather myths do you hear the most? The myth that hot and dry weather causes earthquakes. It is a myth, but our last quake, on St. Patrick's Day 2014 in Hollywood, did follow the hottest day of the year and the hottest day since 14 November 2013.

What is the strangest/most interesting question you've received as a broadcaster? A man in South Texas called our station and asked, "Why do you keep calling that guy a urologist?" We told him that the announcer is saying meteorologist and not urologist! He hung up.

What was the most important way to prepare yourself for this job? In college, they didn't have classes on how to perform, so I took acting classes, voice-over classes, and a few other classes to help me be a better presenter.

James Castillo received his AMS TV Seal of Approval in 1991 and his CBM in 2013. For more information on the Certified Broadcast Meteorologist Program, go to www.ametsoc.org/amscert/index.html#cbm.

Jenni L. Evans, professor of meteorology, has been named acting director of the Penn State Institutes of Energy and the Environment (PSIEE). PSIEE is the central coordinating structure for energy and environmental research at Penn State. Organized under the Office of the Vice President for Research, PSIEE brings together more than 500 faculty, staff, and students to advance the energy and environmental research missions of the university.


Jenni L. Evans

PSIEE's current director, Tom Richard, professor of agricultural and biological engineering, will be on sabbatical from July 2014 through June 2015, during which time Evans will guide PSIEE.

Evans received her bachelor of science (with honors) and doctorate in applied mathematics from Monash University in 1984 and 1990, respectively. She served as visiting scientist with the Naval Postgraduate School in Monterey, California, and as a research scientist with the Commonwealth Scientific and Industrial Research Organization in Melbourne, Australia, before being appointed as an assistant professor of meteorology at Penn State in 1992. Evans was promoted to associate professor in 1998 and to full professor in 2005. She holds a joint appointment in the Earth and Environmental Systems Institute and served as its interim director in 2013.

Evans's research interests are organized around the themes of tropical cyclones, tropical convection, and climate change. She is a member of a small group of scientists who recognized and developed the research area of extratropical transition of tropical cyclones. Recent extratropical transition events of importance to the United States include Hurricane Ivan in 2004, Hurricane Ike in 2008 and, more controversially, Hurricane Sandy in 2012.

The forecasting tool she developed during that effort is actively used by the U.S. and Canadian National Hurricane Centers, as well as by the U.S. Air Force Weather Squadron, the Joint (U.S. Navy/Air Force) Typhoon Warning Center.

Evans's research has been supported by the National Science Foundation, NASA, the EPA, and the U.S. Navy. Since 2003, she has served as the professional team lead meteorologist for the Florida Commission for Hurricane Loss Projection Methodology, and in 2010, she was elected a Fellow of AMS.

Sundar A. Christopher has been appointed dean of The University of Alabama in Huntsville (UAH) College of Science. Christopher currently serves as professor and chairman of the Department of Atmospheric Science in the College of Science. Additionally, he directs the Institute of Remote Sensing Applications, and is associate director of the Earth System Science Center at UAH.


Sundar A. Christopher

He began his tenure with the university in 1997 as an assistant professor in the Department of Atmospheric Science. Christopher was promoted to associate professor in 2001 and was awarded tenure a year later. He became full professor in 2007 and was appointed chairman of the Department of Atmospheric Science in 2010.

Christopher successfully designed a master's-level graduate program in Earth system science that educates and trains graduate students in new paradigms involving research to decision making.

His research interests include satellite remote sensing of clouds and aerosols and their impact on air quality, environment, health, and global and regional climate. He works with numerous satellite datasets from polar orbiting and geostationary satellites, ground-based instruments, and aircraft data to study the Earth–atmosphere system. He has published more than 100 peer-reviewed papers in national and international journals, including several review papers

IN MEMORIAM

VINCENT CARDONE
1941–2014

ALLAN MOLLER
1950–2014

CLIFFORD MURINO
1929–2014

related to aerosols, air quality, and the climate impacts of aerosols.

Christopher has won several million dollars in grants and contracts from NASA, NOAA, and other federal agencies for studying Earth–atmosphere processes. He earned a B.E. in mechanical engineering from Madras University, India, an M.S. in meteorology from The South Dakota School of Mines and Technology, an M.A. in industrial organizational psychology from the University of Alabama in Huntsville, and a Ph.D. in atmospheric science from Colorado State University.

NASA has named **Gavin A. Schmidt** to head the agency's Goddard Institute for Space Studies (GISS) in New York, a leading Earth climate research laboratory.

Currently deputy director of the institute, Schmidt steps into the position left vacant after the retirement of long-time director James E. Hansen and becomes only the third person to hold the post.

Schmidt, an expert in climate modeling, began his career at GISS in 1996. His primary area of research is the simulation of past, present, and future climates. He has worked on developing and improving computer models that integrate ocean, atmosphere, and land processes to simulate Earth's climate, and he is particularly interested in how their results can be compared to paleoclimatic data.

Schmidt received a bachelor's degree in mathematics from Oxford University in 1988 and a doctorate in applied mathematics from University College London in 1994. He came to New York as a 1996 NOAA Postdoctoral Fellow in Climate and Global Change Research.

In addition to more than 100 published, peer-reviewed articles, he is the coauthor of *Climate Change: Picturing the Science*, a collaboration between climate scientists and photographers. In 2011, he was awarded the American Geophysical Union Climate Communications Prize.

POLICY PROGRAM NOTES

PRINCIPLES FOR WEATHER AND CLIMATE LEGISLATION

How the weather and climate community engages the policy process helps determine the impact that legislation has on our community and the broader society. We can help improve policy most effectively when we develop our goals and approaches early in the process and through careful deliberation.

At the broadest level, our goal for all weather and climate legislation must be that it benefits the public. This should be our primary goal because helping the broader society is our primary mission. Legislation that fails in this respect is inconsistent with our values and goals and therefore simply isn't worthy of our support. Indeed, legislation that at first seems to benefit our community—but that comes at the expense of the broader society—is actually harmful to us because our credibility, our standing, and the reason our voice is heard is due to our commitment to serving the broader society and to our considerable success in doing so.

Of course, our goals for legislation must also include that it help the weather and climate community. This should be interpreted broadly (i.e., for us overall) rather than narrowly (i.e., for specific subgroups only). We are most effective as a cohesive unit. Furthermore, advances in all aspects of our work (weather and climate; basic and applied research; observations, science, and services) are needed to achieve the full potential that we can provide the broader society.

Legislation that focuses narrowly on one aspect of our work is fine—as long as it doesn't come at the expense of another part of our community. We must be cognizant of political myopia and narrowly focused interests, which sometimes set up a zero-sum game with gains in one area coming at the expense of another. A good general rule is that advances in one area must include no adverse impacts in other areas of the community.

There may also be times when policy priorities shift or when legislative options involve difficult choices and trade-offs. The best trade-offs to make and the most appropriate balances to strike are almost never unambiguously clear. If you wish to contribute to that discussion, then a good rule of thumb is that the sacrifices you call for should begin at home. Anyone who feels their own work is unnecessary should feel free to call for zeroing it out of the budget or to demand that policymakers ignore it when writing legislation. But it generally isn't credible for us to ask for someone else to sacrifice so that we may benefit.

The responsibility for making those difficult choices needs to be handled carefully and exercised responsibly. Institutions and individuals that get involved must follow a decision-making process that strives for fairness and legitimacy. Generally, that involves broad sharing of sacrifices (in the rare instances when sacrifices are truly necessary) and making decisions that are based on broad input from all relevant members of the community.

Legislation would benefit both our community and the broader society if it advances observations and science that improve knowledge and understanding of weather events and the climate system; establishes or improves services and regulations related to weather and climate risks and opportunities, or; improves or streamlines scientific practices.

For example, additional funding would provide resources needed to maintain and expand observations and to increase the number of experts focused on weather and climate challenges. Legislation that promotes responsive, nonpartisan oversight, that minimizes political interference, and that empowers scientists to accomplish their work can help keep weather and climate experts focused on what they do best: making critical scientific breakthroughs and applying them to the benefit of society. This would make it possible for new advances to occur more quickly and be applied more effectively.

In contrast, policies (and efforts to help shape them) are more likely to be harmful when not thought through carefully or when driven by politics rather than substantive merit. Funding cuts and disruptive interference with weather and climate science and services will harm society's disaster preparedness and response capabilities.

Developing a strategy to help achieve positive legislative outcomes depends on identifying potential advances in weather and climate, understanding the legislative options that can make those advances possible, and communicating both effectively to policymakers.

Critically, we must be prepared to contribute throughout the legislative process as opportunities arise—particularly at stages of legislative development when large changes are possible—not just at the end when legislation has matured and is ready for votes. This takes proactive efforts and discipline on our part because the impacts of legislation—positive and negative—will seem distant and remote when our issues aren't under active consideration. Fortunately, planning ahead is a core strength of the weather and climate community—preparedness and response is what we do, after all. If we can apply that to the policy process, we can contribute to legislation in ways that enhance our community's ability to provide the information and services the nation (and the world) needs to manage risks and realize opportunities associated with weather, water, and climate.

Legislation that increases funding for observations, science, and services; improves the practice of science; enhances the provision of services; or improves the regulatory management of risks, would help create new business opportunities and enable social and economic advancements that could not otherwise occur. Our efforts to engage the policy process can help make these positive outcomes possible, but only if we have a clear understanding of our goals and a well-thought-out strategy for achieving them.

—Paul Higgins, AMS Policy Program Director

2014 AMS Graduate Fellowship Recipients

AMS is pleased to announce the recipients of the 2014 AMS Graduate Fellowships.

The AMS graduate fellowship program, supported by industry and government agencies, is designed to recruit promising young people entering their first year of graduate study from a wide range of interests: meteorology, physics, mathematics, hydrology, oceanography, marine science, computer science, and engineering. The program has two goals: the first is to help ensure that outstanding young scientists enter the fields of atmospheric, oceanic, and hydrologic science; the second is to provide sufficient resources to allow each recipient to pursue a full schedule of academic studies during the first year of graduate study, which will place them in a position to make contributions to their chosen field sooner. The fellowship includes a $24,000 stipend and travel support to attend the AMS annual meeting.

Fellowship applicants must submit a completed application form, two written essays, three faculty recommendations, GPA scores, and an official transcript. Fellowship recipients are selected for their academic excellence, community involvement and volunteer efforts, and their ability to demonstrate why they should receive a fellowship and their future career plans in the sciences. AMS, in conjunction with the sponsors, have been awarding graduate fellowships since 1991. Since its inception date, AMS has awarded 330 fellowships with the dollar amount totaling over $7 million.

A very special thank you goes out to the sponsors that make the graduate fellowship program possible.

Lockheed Martin Corporation

DOE Atmospheric System Research

NASA Earth Science (supporting four fellowships)

NOAA's National Weather Service

AMS 21st Century Campaign (supporting three fellowships)

LOCKHEED MARTIN CORPORATION FELLOWSHIP

Elizabeth N. Smith has been awarded the Lockheed Martin Corporation Fellowship. Ms. Smith graduated with a B.S. in meteorology from The California University of Pennsylvania. She will pursue a M.S. in meteorology at the University of Oklahoma. Ms. Smith is interested in mesoscale and storm scale meteorology. Her graduate research will involve the Plains Elevated Convection At Night (PECAN) field project, working under Drs. Petra Klein and Evgeni Fedorovich. She will investigate pre-storm environments and low-level jets.

DOE ATMOSPHERIC SYSTEM RESEARCH FELLOWSHIP

Isabel L. McCoy has been awarded the DOE Atmospheric System Research Fellowship. Ms. McCoy graduated with a B.S. in physics from New Mexico Institute of Mining and Technology. She will pursue a M.S. in atmospheric sciences at the University of Washington. Ms. McCoy is interested in climate, clouds, radiation, and large-scale atmospheric dynamics. Her research will involve the intersection of clouds and large-scale atmospheric dynamics. She is particularly interested in the radiative impacts of clouds and cloud and aerosol feedbacks.

AMS GRADUATE FELLOWSHIP IN THE HISTORY OF SCIENCE

Joseph Giacomelli has been awarded the AMS Graduate Fellowship in the History of Science. Mr. Giacomelli graduated with a B.A. in history and geography from Middlebury College in 2008 and is pursuing a Ph.D. in history from Cornell University. His thesis is entitled, *Uncertain Climes: Human Agency and Climate Change in Late Nineteenth-Century America*. "My dissertation focuses on late nineteenth-century climate science in the United States. I am interested in the scientists, surveyors, and boosters who argued over the role of human agency in modifying the climate of the Great Plains and Intermountain West. By examining scientific reports, pamphlets, and maps produced over the course of the climate debate, I hope to connect climate history to broader themes such as industrialization, settlement, and Native American history. My project is especially concerned with the issue of uncertainty. I will examine the role of scientific uncertainty in the climate debate while also exploring the relationship between this uncertainty and the cultural doubts lurking within Manifest Destiny."

The 2014 AMS Graduate Fellowship in the History of Science is awarded to a student in the process of completing a dissertation on the history of the atmospheric or related oceanic or hydrologic sciences. The fellowship carries a $15,000 stipend and supports one year of dissertation research. The goal of the graduate fellowship is to generate a dissertation topic in the history of the atmospheric, or related oceanic or hydrologic sciences, and to foster close working relations between historians and scientists. Fellowships are available to graduate students in good standing who propose to complete a dissertation as described above.

NASA EARTH SCIENCE FELLOWSHIP

Kevin A. Biernat has been awarded the NASA Earth Science Fellowship. Mr. Biernat graduated with a B.S. in meteorology from Central Michigan University. He will pursue a M.S. in atmospheric science at the State University of New York at Albany. Mr. Biernat is interested in synoptic and mesoscale meteorology; and during graduate school will study these areas including tropical meteorology. Ultimately he plans to pursue academia to obtain a professorship in the field of atmospheric sciences, which will also allow him to continue completing research.

NASA EARTH SCIENCE FELLOWSHIP

Michelle E. Frazer has been awarded the NASA Earth Science Fellowship. Ms. Frazer graduated with a B.S. in physics from Cedarville University. She will pursue a M.S. in atmospheric and oceanic sciences at Princeton University. Ms. Frazer is interested in modeling application of clouds and aerosols. Her graduate research will focus on the impact of clouds/aerosol interactions in global climate models.

NASA EARTH SCIENCE FELLOWSHIP

Jessica Haskins has been awarded the NASA Earth Science Fellowship. Ms. Haskins graduated with a B.S. in earth, atmospheric and planetary sciences from Massachusetts Institute of Technology. She will pursue a M.S. in atmospheric science at the University of Washington. Ms. Haskins is interested in atmospheric chemistry modeling and measurement. She will be working with Prof. Joel Thornton on her graduate research, which will begin with using a combined satellite-lightning network–radar suite to examine the role that lightening from isolated thunderstorms may play as a driver of upper-tropospheric NOx over the United States.

NASA EARTH SCIENCE FELLOWSHIP

Andrew R. Wade has been awarded the NASA Earth Science Fellowship. Mr. Wade graduated with a B.S. in meteorology from the University of Oklahoma (OU). He will continue at OU and pursue a M.S. in meteorology. Mr. Wade will be working with Dr. Mike Coniglio of the National Severe Storms Lab to examine supercell–environment interactions using sounding data from the Mesoscale Predictability Experiment (MPEX). His hope for the future is to continue research in the area of severe weather and become a faculty member in a major meteorology or atmospheric science program.

NOAA NATIONAL WEATHER SERVICE FELLOWSHIP

Dana M. Mueller has been awarded the NOAA Weather Service Fellowship. Ms. Mueller graduated with a B.S. in meteorology from the University of Oklahoma. She will pursue a M.S. degree in atmospheric science at the University of Wyoming. Ms. Mueller will focus her research on the Plains Elevated Convection at Night (PECAN) experiment. She will be working on UW King Air and Tq Raman lidar observations of bores. Her primary interest is the application of atmospheric science to other industries, particularly aviation. After graduating, Ms. Mueller will seek employment in the private sector.

AMS 21ST CENTURY CAMPAIGN FELLOWSHIP

Castle A. Williams has been awarded the AMS 21st Century Campaign Fellowship. Mr. Williams graduated with a B.S. in geography and psychology from The University of Georgia (UGA). He will continue at UGA and pursue a M.S. in geography. Mr. Williams is interested in social sciences and atmospheric sciences. His graduate studies will focus on research that deals with bridging the gap between social sciences and atmospheric sciences in an attempt to thoroughly communicate weather and climate information to the general public. His future career goals include conducting research that involves related topics for overall communication of weather, in hopes of working toward the complete integration of both the meteorological and psychological fields.

THE FATHER JAMES B. MACELWANE ANNUAL AWARD

Sharon M. Sullivan has been awarded the AMS Father James B. Macelwane Award. Ms. Sullivan graduated with a B.S. in applied mathematics from the University of Mexico in May 2014 and will pursue a M.S. in atmospheric science at the University of Wyoming. The paper was written in her senior year under the direction of Dr. David Gutzler. Her paper is entitled: "The 1941 Project: A Meteorological Reanalysis Investigation into an Abnormal Year of Precipitation." Ms. Sullivan states that the 1941 project is an observational investigation of the wettest year on record in New Mexico. She obtained her data by using many different variables and climatic indices, basic statistical analysis, precipitation records, and a large-scale dataset generated from a twentieth century "reanalysis."

The Father James B. Macelwane Annual Award was established by the American Meteorological Society to honor the late Rev. James B. Macelwane, S.J., a world renowned authority of seismology, who was a geophysicist and Dean of the Institute of Technology, Saint Louis University, until his death in 1956. The award carries a $1,000 stipend, supported by member donations to the AMS. The purpose of this award is to stimulate continued interest in the atmospheric and related sciences among college students through the encouragement of original student papers concerned with some phase of the atmospheric sciences. The student must be enrolled as an undergraduate at the time the paper is written, and no more than two students from any one institution may enter papers in any one contest.

2014 GRADUATE FELLOWSHIP SPONSORS

LOCKHEED MARTIN CORPORATION

Lockheed Martin Corporation (LMC), headquartered in Bethesda, Maryland, has a long history of service to the meteorological and environmental community. LMC built and launched the world's first weather satellite, *TIROS I*, in 1960 and since that time has deployed over 100 satellites (accommodating over 600 instruments) to observe the Earth and the sun, including all of the NOAA and Defense Department polar-orbiting operational satellites (POES and DMSP). Continuing this proud heritage, in 2009 LMC was awarded the contract to build the spacecraft for the latest generation of the Geostationary Operational Environmental Satellite series R (GOES-R). LMC also builds instruments that satellites carry, such as the Cryogenic Limb Array Etalon Spectrometer (CLAES) that flew on the Upper Atmosphere Research Satellite and detected chlorofluorocarbons (CFCs) in the stratosphere, and the Solar X-ray imager (SXI) flying on the current GOES satellites. For GOES-R LMC is building two new instruments: the solar ultraviolet imager (SUVI) and the geostationary lightning mapper (GLM). LMC is also a world leader in ground-based weather systems, including the NEXRAD weather surveillance radar deployed at over 150 sites in this country and abroad, the tropospheric wind profiler radar deployed at over 35 sites in this country, and more recently, laser radar systems designed to detect wind shear and wake vortex conditions at airports. The Corporation builds a range of meteorological and oceanographic sensors, including expendable probes that collect data on the physical properties of the ocean and upper atmosphere, which are used by the National Weather Service and other customers. Exploiting data gathered by meteorological sensors requires integrated weather systems and in this arena LMC provides systems to the Department of Defense and civil agencies to ingest environmental data from low-earth-orbiting and geostationary satellites, both domestic and international, and generate analysis and forecast products. Integrated system solutions are also provided for international customers such as the National Integrated Meteorological and Hydrological Forecast Systems for Romania. Lockheed Martin is a total system provider with a proud heritage—and we never forget who we're working for.

DOE ATMOSPHERIC SYSTEM RESEARCH

Atmospheric System Research (ASR), one of the global climate research programs of the U.S. Department of Energy (DOE) Office of Science, strives to resolve scientific uncertainties related to atmospheric climate processes. Managed by DOE's Office of Biological and Environmental Research, the ultimate goal of ASR is to improve the treatment of cloud, aerosol, and radiation physics in regional and global climate models in order to improve the climate simulation capabilities of these models.

The ASR Program promotes the usage of atmospheric measurements at permanently instrumented DOE Atmospheric Radiation Measurement (ARM) research sites at locales representative of the Earth's major climate regimes. Three ARM Mobile Facility units with many of the same capabilities as the fixed sites also gather atmospheric data for a period of up to 18 months at selected geographic locations. ARM measurements allow ASR scientists to research a broad range of issues that span surface-based remote sensing, physical process investigation, and modeling of cloud, aerosol, and radiation processes. The ASR science team has made significant contributions to radiative transfer theory and applications, ground-based remote sensing of cloud and aerosol properties, cloud process modelling, and cloud and radiation parameterizations for global climate models. Many new science components in the Community Earth System Model (CESM) were developed by ASR scientists.

ASR research activities are carried out at national laboratories, universities, and private institutions, and are selected through competitive, merit review processes.

NASA EARTH SCIENCE

NASA's Earth Science Research Program supports research activities that address the Earth system to characterize its properties on a broad range of spatial and temporal scales, to understand the naturally occurring and human-induced processes that drive them, and to improve our capability for predicting its future evolution. The focus of the Earth Science Research Program is the use of space-based measurements to provide information not available by other means. NASA's program is an end-to-end endeavor that starts with the development of observational techniques and the instrument technology needed to implement them; tests them in the laboratory and from an appropriate set of surface-, balloon-, aircraft-, and/or space-based platforms; uses the results to increase basic process knowledge; incorporates results into complex computational models that can be used to more fully characterize the present state and future evolution of the Earth system; and develops partnerships with other national and international organizations that can use the generated information in environmental forecasting and in policy, business, and management decisions.

The basic research and analysis activities are structured around six interdisciplinary focus areas that interconnect with each other; these focus areas are carbon cycle and ecosystems, water and energy cycle, climate variability and change, atmospheric composition, weather, and Earth surface and interior. NASA also supports applied research with current emphasis on water resources, health and air quality, disasters, weather, and ecological forecasting.

NASA sponsors four AMS/Industry/Government Graduate Fellowships each year. NASA places particular emphasis on the applicant's ability and interest in pursuing academic training and research in Earth system science with a focus on space-based measurements. For a more detailed description of the NASA Earth Science Research Program, please see Chapter Four of the *NASA Science Plan* at http://science.nasa.gov/about-us/science-strategy/.

NOAA'S NATIONAL WEATHER SERVICE: BUILDING A WEATHER-READY NATION

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) provides weather, water, and climate forecasts and warnings for the United States, its territories, adjacent waters, and ocean areas, for the protection of life and property and the enhancement of the national economy. NWS data and products form a national information database and infrastructure that is used by other governmental agencies, the private sector, the public, and the global community.

Over the past few years, extreme weather, water, and climate events have hit communities across the country with devastating and tragic results; all the while, forecast accuracy continues to improve. It is clear that more has to be done. NOAA's Weather-Ready Nation strategic goal is the agency's response to minimizing the loss of life and disruption of livelihoods.

Building a Weather-Ready Nation (WRN) not only means delivering better forecasts and warnings—timing, intensity, and expected impacts—it is about making the forecasts and warnings easier to understand and actionable for stakeholders such as emergency managers and more broadly for the public. The National Weather Service continues to explore ways to enhance decision support services to enhance the nation's preparedness. NOAA's Office of Oceanic and Atmospheric Research and National Environmental Satellite, Data, and Information Service are moving new science and technology into operations, which will improve forecasts, increase lead times, and ultimately increase weather-readiness.

Building a Weather-Ready Nation starts with these internal actions, but NOAA and the National Weather Service can't build a Weather-Ready Nation alone. It requires the action of a vast nationwide network of partners including government agencies, emergency managers, researchers, the media, insurance industry, nonprofits, businesses, and the entire Weather Enterprise.

That is why in early 2014, NOAA launched the Weather-Ready Nation Ambassador initiative. This initiative is NOAA's commitment to working with organizations to make our country ready, responsive, and resilient to extreme events. WRN Ambassadors are helping NOAA move the bar even higher whether by using NOAA data to generate and deliver valuable lifesaving information, or from the user side, taking a leadership role within their respective community and engaging their stakeholders to be ready, responsive, and resilient.

A "Weather-Ready Nation" is a strategic outcome where there is effective management of the nation's water supply, full understanding of climate-related risks, enhanced economic productivity, healthy ecosystems, and resilient communities. NOAA's NWS by the Numbers: nearly 5,000 dedicated people work in 122 weather forecast offices, 13 river forecast centers, 9 national centers, 2 tsunami warning centers, and other support offices around the United States and its territories. Each year, NWS collects some 76 billion observations and issues approximately 1.5 million forecasts and 50,000 warnings.

AMS 21ST CENTURY CAMPAIGN

The AMS 21st Century Campaign provides a focused institutional mechanism for AMS members, and organizations involved in the atmospheric and related sciences and services, to make meaningful contributions to the advancement of their science and to societal betterment. This campaign theme parallels and supports the goals of the AMS 10-Year Vision, which is to employ the remarkable advances in the atmospheric and related sciences and services for the benefit of society as a whole. The campaign is centered around four program areas:

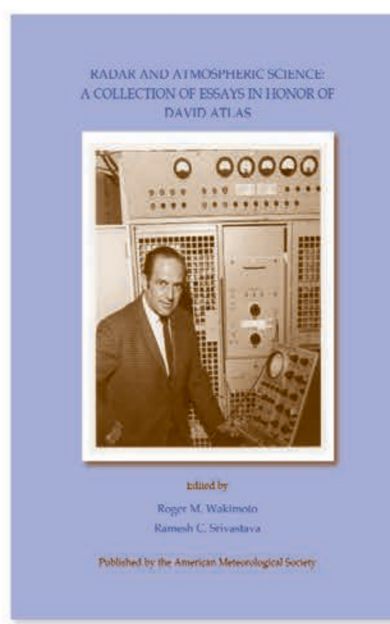
- **AMS Policy Program**—working to strengthen the connection between public policy and Earth system science and services by building policy research and by creating opportunities for policymakers and scientists to engage and exchange perspectives to foster better-informed policy decisions
- **Education**—The AMS Fellowship and Scholarship Programs assist students pursuing degrees in the atmospheric and related sciences. AMS relies on support of its members and an array of private sector and government agencies to fund the fellowships and scholarships. AMS is also a strong advocate of providing educational opportunities for students within the framework of scientific conferences. Contributions to the Education Fund also help support student travel to AMS meetings and the implementation of the AMS Student Conference, which has more than 500 student attendees each year.
- **Teacher Training Enhancement**—The AMS K–12 Education Program works to promote interest and literacy in science, mathematics, and technology at a very early age, and strives to maintain a network of well-trained teachers supplied with quality instructional resource materials. AMS has built widely recognized K–12 teacher enhancement initiatives that are making a difference in upgrading public scientific literacy on a national scale. The AMS Education Program actively seeks individual and corporate support to assure that its exemplary teacher enhancement programs continue to thrive and reach teachers throughout the United States.
- **History of the Atmospheric and Related Sciences**—projects aimed at gathering, preserving, and providing access to historical documentation in science and technology.
- **Public Awareness**—focusing on increasing the visibility of AMS in both the atmospheric sciences community and in areas outside of our own field.

Through the support of member contributions to the AMS 21st Century Campaign, AMS is able to award minority scholarships and graduate fellowships to outstanding individuals pursing degrees in the atmospheric and related sciences.

Radar and Atmospheric Science: A Collection of Essays in Honor of David Atlas

Edited by Roger M. Wakimoto and Ramesh Srivastava

This monograph pays tribute to one of the leading scientists in meteorology, Dr. David Atlas. In addition to profiling the life and work of the acknowledged "Father of Radar Meteorology," this collection highlights many of the unique contributions he made to the understanding of the forcing and organization of convective systems, observation and modeling of atmospheric turbulence and waves, and cloud microphysical properties, among many other topics. It is hoped that this text will inspire the next generation of radar meteorologists, provide an excellent resource for scientists and educators, and serve as a historical record of the gathering of scholarly contributions honoring one of the most important meteorologists of our time.



Radar and Atmospheric Science:
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AMS BOOKS

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2014 AMS Minority Scholarship Recipients

AMS is pleased to announce the 2014 AMS Minority Scholarship recipients.

The AMS Minority Scholarship Program is intended to encourage minority students, who have been traditionally underrepresented in the sciences, especially Hispanic/Latino, American Indian/Alaska Native, and Black/African American students, to pursue careers in the atmospheric and related oceanic and hydrologic sciences. The two-year scholarships include a $6,000 stipend ($3,000 per freshman and sophomore year) and travel support to attend the AMS annual meeting while in their junior year of studies.

Awards are based on academic merit, faculty recommendations, and a written essay that demonstrates their desire to enter into an atmospheric or related science. AMS thanks its members for their generous contributions that support this very worthwhile program.

AMS 21st Century Campaign

AMS 21ST CENTURY CAMPAIGN SCHOLARSHIP

Ade A. Samuel is a graduate of Herndon High School in Herndon, Virginia. He will be majoring in chemical engineering, focusing on the development of alternative fuels, at the Massachusetts Institute of Technology.

AMS 21ST CENTURY CAMPAIGN SCHOLARSHIP

Elijah M. Staple is a graduate of Longmont High School in Longmont, Colorado. He will be majoring in computer science, focusing on the improvement of weather predictions, at the University of Colorado—Boulder.

AMS 21ST CENTURY CAMPAIGN SCHOLARSHIP

John M. Toohey is a graduate of Ransom Everglades High School in Coconut Grove, Florida. He will be majoring in atmospheric science and minoring in environmental science and sustainability at Cornell University.

2014 MINORITY SCHOLARSHIP SPONSORS

AMS 21ST CENTURY CAMPAIGN

The AMS 21st Century Campaign provides a focused institutional mechanism for AMS members, and organizations involved in the atmospheric and related sciences and services, to make meaningful contributions to the advancement of their science and to societal betterment. This campaign theme parallels and supports the goals of the AMS 10-Year Vision, which is to employ the remarkable advances in the atmospheric and related sciences and services for the benefit of society as a whole. The campaign is centered around four program areas:

- **AMS Policy Program**—working to strengthen the connection between public policy and Earth system science and services by building policy research and by creating opportunities for policymakers and scientists to engage and exchange perspectives to foster better-informed policy decisions
- **Education**—The AMS Fellowship and Scholarship Programs assist students pursuing degrees in the atmospheric and related sciences. AMS relies on support of its members and an array of private sector and government agencies to fund the fellowships and scholarships. AMS is also a strong advocate of providing educational opportunities for students within the framework of scientific conferences. Contributions to the Education Fund also help support student travel to AMS meetings and the implementation of the AMS Student Conference, which has more than 500 student attendees each year.
- **Teacher Training Enhancement**—The AMS K–12 Education Program works to promote interest and literacy in science, mathematics, and technology at a very early age, and strives to maintain a network of well-trained teachers supplied with quality instructional resource materials. AMS has built widely recognized K–12 teacher enhancement initiatives that are making a difference in upgrading public scientific literacy on a national scale. The AMS Education Program actively seeks individual and corporate support to assure that its exemplary teacher enhancement programs continue to thrive and reach teachers throughout the United States.
- **History of the Atmospheric and Related Sciences**—projects aimed at gathering, preserving, and providing access to historical documentation in science and technology.
- **Public Awareness**—focusing on increasing the visibility of AMS in both the atmospheric sciences community and in areas outside of our own field.

Through the support of member contributions to the AMS 21st Century Campaign, AMS is able to award minority scholarships and graduate fellowships to outstanding individuals pursing degrees in the atmospheric and related sciences.

2014 AMS Freshman Undergraduate Scholarship Recipients

AMS is pleased to announce the recipients of the 2014 AMS Freshman Undergraduate Scholarships.

The AMS Freshman Undergraduate Scholarship Program is open to high school students pursuing an undergraduate degree in the atmospheric or related oceanic or hydrologic sciences. The scholarships are sponsored by industry and through the support of AMS members. The sponsors of these scholarships recognize the importance of encouraging young people to pursue a career in the AMS-related sciences.

Awards are based on academic merit, faculty recommendations, and a written essay that demonstrates their desire to enter into an atmospheric or related sciences academic program. The two-year scholarships include a $5,000 stipend ($2,500 per freshman and sophomore year) and travel support to attend the AMS annual meeting while in their junior year.

AMS thanks the individuals and organizations that have contributed to the AMS Freshman Undergraduate Scholarship program.

INDUSTRY AND GOVERNMENT SPONSORS

Science and Technology Corporation

Baron Services, Inc.

Lockheed Martin Mission Systems and Sensors (MS2)

Vaisala, Inc.

SAIC/Center for Atmospheric Physics

Earth Networks—Owner of the WeatherBug Brand of Products and Solutions

Stinger Ghaffarian Technologies

Naval Weather Service Association

NAMED SCHOLARSHIPS

The Percival D. Wark and Clara B. (Mackey) Wark Endowed Scholarship

The Bernard Vonnegut and Vincent Schaefer Endowed Scholarship

The Edgar J. Saltsman Endowed Scholarship

The scholarship awardees are attending the following universities: Duke University, The University of North Carolina, Brown University, The University of Oklahoma, The University of Illinois, Texas A&M University, State University of New York—Oswego, Millersville University, Colorado College, The Pennsylvania State University, and Stanford University.

SCIENCE AND TECHNOLOGY CORPORATION SCHOLARSHIP

Tyler M. Fenske is a graduate of Cinco Ranch High School in Katy, Texas. He will major in meteorology at Texas A&M University.

EARTH NETWORKS—WEATHERBUG SCHOLARSHIP

Sean R. Ernst is a graduate of F. W. Parker Charter School in Devens, Massachusetts. He will major in meteorology at the University of Oklahoma.

BARON SERVICES, INC. SCHOLARSHIP

Travis B. Broadhurst is a graduate of North Buncombe High School in Weaverville, North Carolina. He will major in physics at the University of North Carolina at Chapel Hill.

STINGER GHAFFARIAN TECHNOLOGIES SCHOLARSHIP

Jacqueline M. Nugen is a graduate of York Community High School in Elmhurst, Illinois. She will major in meteorology at the University of Oklahoma.

LOCKHEED MARTIN MISSION SYSTEMS & TRAINING SCHOLARSHIP

Madison A. Barne is a graduate of Panther Creek High School in Cary, North Carolina. She will major in environmental science and policy at Duke University.

NAVAL WEATHER SERVICE ASSOCIATION SCHOLARSHIP

Alexander M. Tomoff is a graduate of St. Edward High School in Lakewood, Ohio. He will major in atmospheric sciences at the Pennsylvania State University.

VAISALA SCHOLARSHIP

Sierra M. Melton is a graduate of Fairview High School in Boulder, Colorado. She will major in geology at Colorado College.

THE PERCIVAL D. WARK AND CLARA B. (MACKEY) WARK ENDOWED SCHOLARSHIP

Thomas E. Collins is a graduate of Chagrin Falls High School in Chagrin Falls, Ohio. He will major in geology–chemistry and computer science at Brown University.

SAIC CENTER FOR ATMOSPHERIC PHYSICS SCHOLARSHIP

Alexander J. Erwin is a graduate of Freeburg Community High School in Freeburg, Illinois. He will major in atmospheric sciences at the University of Illinois.

THE PERCIVAL D. WARK AND CLARA B. (MACKEY) WARK ENDOWED SCHOLARSHIP

Kevin C. Larson is a graduate of Five Oaks Academy in Greer, South Carolina. He will major in atmospheric science at Texas A&M University.

THE BERNARD VONNEGUT AND VINCENT SCHAEFER ENDOWED SCHOLARSHIP

Amber J. Liggett is a graduate of Lincoln Park Performing Arts Charter School in Beaver, Pennsylvania. She will major in meteorology and oceanography at Millersville University.

EDGAR J. SALTSMAN ENDOWED SCHOLARSHIP

Yu (Catherina) Xu is a graduate of Homestead High School in Cupertino, California. She will major in earth systems at Stanford University.

EDGAR J. SALTSMAN ENDOWED SCHOLARSHIP

Zachary A. Hiris is a graduate of Van Buren High School in Van Buren, Ohio. He will major in meteorology at the State University of New York at Oswego.

2014 FRESHMAN UNDERGRADUATE SCHOLARSHIP SPONSORS

SCIENCE AND TECHNOLOGY CORPORATION

Science and Technology Corporation (STC) is an innovative, private company founded by Dr. Adarsh Deepak in 1979. Our highly qualified staff provides scientific and technical support services to the U.S. Government (NASA, NOAA, DoD, and other agencies), industry, and international organizations at 20 locations across the United States and in Europe.

STC is a leader in numerous aspects of atmospheric sciences and related remote sensing research, to include

- Meteorological satellite data processing and analysis
- Modeling and analysis of clouds, aerosols, ozone, and atmospheric gases
- Radiation propagation studies
- Global and mesoscale model development
- Air quality forecast improvements

In addition, we have a distinguished record of providing superb management support for Earth science program activities. Current/recent atmospheric science support activities include

- NOAA's Office of Oceanic and Atmospheric Research (OAR)
- National Environmental Satellite Data and Information Service (NESDIS)
- National Weather Service (NWS)
- Office of the Federal Coordinator for Meteorology (OFCM)
- International Global Energy and Water Cycle Experiment (GEWEX) Project Office

Beyond our strength in atmospheric sciences, STC has several other scientific and technical capabilities of excellence, to include

- Multidisciplinary scientific software development, to include High-Performance Computing (HPC)
- Instrument systems design, development, fabrication, implementation, and calibration for ground, satellite, airborne, and ship platforms
- Computational Fluid/Structural Dynamics (CFD/CSD) modeling for advanced rotorcraft and NASA spacecraft
- Polar and cold regions technology applications
- Naval architecture for design and testing of icebreaking ships
- Electronic, mechanical, composite, and machining fabrication of NASA flight-certified and ground support equipment and test articles
- Chemical and biological demilitarization, monitoring, and laboratory activities
- Developmental and operational testing and evaluation
- Small-satellite design, development, and fabrication

BARON SERVICES, INC.

Baron provides meteorologists and businesses with tools and data that improve safety in environments where the need for weather awareness is critical.

Our technology is relied upon by everyone in the United States with a need for weather information. In partnership with L-3 STRATIS, we upgraded the country's NEXRAD radar network to dual-polarization, allowing National Weather Service, Department of Defense and Federal Aviation Administration meteorologists to analyze and forecast weather in ways never before possible. Baron also works other national weather agencies to provide radar solutions.

Leading private research in dual-polarization weather radar, we have developed value-added data products for accurate, hyper-local analysis of inclement conditions. A staff of data services meteorologists and scientists works continuously to develop innovative technologies and further Baron research.

We believe that weather precision matters. Our storm tracking and display technologies, forecast modeling, and data distribution capabilities allow Baron customers to reach their audiences with accurate, hyper-local weather data, benefitting those critically impacted by weather.

Baron has built successful relationships with leaders in media, marine, aviation, mobile and tablet apps, automotive, and more. Our relationship with SiriusXM allows us to provide pilots, boaters, and storm chasers with graphical datalink weather in mobile environments. Consumers use our information to improve situational awareness and decision-making. Additionally, our patented technology powers the XM NavWeather service, which provides road weather information to drivers in a safe, convenient manner, allowing them to take the safest, most efficient routes.

With over 30 patents for collecting, interpreting, and displaying accurate weather data for those who depend on it, Baron has extensive experience in delivering trusted analysis to industries where the need for superior weather intelligence is critical.

LOCKHEED MARTIN MISSION SYSTEMS & TRAINING)

Lockheed Martin Mission Systems & Training (MST) provides systems engineering, software development and complex program management for global security, civil and commercial markets. MST executes nearly 500 programs for the U.S. Navy, Coast Guard, Air Force, Army, and Marine Corps, as well as industrial, research, and commercial customers in 50 nations.

The company's Marion, Massachusetts, facility has a proud heritage of more than 60 years in the development and production of specialized instrumentation for environmental observations. Hundreds of customers around the world including NOAA, all U.S. Department of Defense agencies, and meteorological/oceanographic services around the world rely on our expendable instrumentation to understand global climate challenges. The MST Marion operation provides advanced GPS upper-air sounding systems for synoptic and research atmospheric measurements, from the surface to the upper atmosphere. Our oceanographic instrumentation and data acquisition systems enable users to obtain real-time profiles of ocean temperature, current velocity, and salinity.

Headquartered in Bethesda, Maryland, Lockheed Martin is a global security and aerospace company that employs approximately 113,000 people worldwide and is principally engaged in the research, design, development, manufacture, integration and sustainment of advanced technology systems, products, and services. The Corporation's net sales for 2013 were $45.4 billion.

Lockheed Martin is proud to support the American Meteorological Society and its AMS Freshman Undergraduate Scholarship Program. We wish this year's recipients all the best.

VAISALA, INC.

Vaisala contributes to a better quality of life by providing a comprehensive range of innovative observation and measurement products and services for meteorology, other weather-related applications, and controlled environments. Vaisala is recognized the world over for its contribution to the development, manufacturing, and marketing of high-quality sensors, instruments, systems, and services to solve measurement and observation needs. For over 75 years, our strong customer focus, combined with reliability and convenience, provides our partners and customers distinct performance advantages and cost savings from the total solutions that we can deliver.

Vaisala is committed to measuring environments of all proportions, from the Earth's atmosphere to the inside of an engine. Striving for worldwide market leadership in selected businesses, our competitive edge lies in product leadership. We are global market leaders in upper-air observations; airport weather observation equipment; road weather observation systems; surface weather measuring networks; lightning detection data networks and instruments; and in professional equipment for measuring relative humidity, dewpoint, CO_2, and barometric pressure. High continual investment in research and development guarantees that Vaisala products are in the forefront of environmental measurement technology.

Therefore, it is again with great pleasure that Vaisala provides a scholarship to individuals who share our company's enthusiasm and commitment toward the science of meteorology.

SAIC, CENTER FOR ATMOSPHERIC PHYSICS

SAIC is a leading technology integrator providing full life-cycle services and solutions in the technical, engineering, and enterprise information technology markets. Our deep domain knowledge and customer relationships enable the delivery of systems engineering and integration offerings for large, complex government and commercial projects. SAIC serves customers in the U.S. federal government, state/local, and global commercial markets, specializing in providing a broad range of higher-end, differentiated technical capabilities.

SAIC is looking for ambitious, tech-savvy college graduates who want to take on the challenge of solving some of the world's most critical problems. Our culture stresses strong commitment to our communities and the environment and to diversity and inclusiveness. You'll also find that our career development and training resources will help you launch your professional career, while enabling you to achieve your personal goals.

We are involved in critical aspects of science, technology, and business. What we do matters to people, nations, and the world in areas of national security, critical infrastructure, health, energy, and the environment. Learn more about what our people do at www.saic.com.

EARTH NETWORKS—WEATHERBUG

Earth Networks, the owner of the popular WeatherBug® brand, will again sponsor an AMS Freshman Undergraduate Scholarship for the 2014/2015 school year. Since 1993, Earth Networks has deeply invested in the education sector and remains firmly committed to inspiring the next generation of climate scientists and meteorologists.

Earth Networks pioneered the WeatherBug Schools program that installs and networks professional-grade weather stations atop thousands of schools. Real-time data from these stations enable teachers to utilize live weather information in the classroom when teaching core science, technology, engineering and math (STEM) courses and lessons on other key topics, such as geography, severe weather, and the environment. While WeatherBug engages young minds in the classroom, WeatherBug also helps protect students during outdoor recess and sports activities with state-of-the-art lightning detection and alerting products that warn of danger via mobile phones, desktop tools, and outdoor sirens.

Twenty years after its founding, Earth Networks is "Taking the Pulse of the Planet" with the world's largest weather observation and lightning detection networks to keep consumers, businesses, and governments informed, updated, and alerted. The WeatherBug brand, which includes award-winning mobile apps for smartphones and tablets, desktop apps, and website (www.weatherbug.com), helps millions Know Before™ with neighborhood-level weather information, pinpoint forecasts, the fastest severe weather alerts, and minute-by-minute, mile-by-mile lightning detection.

Earth Networks' lightning data is used by the NWS, the Air Force Weather Agency, and NASA's Wallops Flight Facility in research, operations, and planning. The company's enterprise solutions support utilities, schools, professional sports teams and leagues, emergency response crews, airports, government entities, and others in safeguarding lives, preparing for weather events, and optimizing business operations. Learn more at www.earthnetworks.com. Get your weather at www.weatherbug.com. Follow Us on Twitter @WeatherBug and Like Us at www.facebook.com/WeatherBug.

STINGER GHAFFARIAN TECHNOLOGIES (SGT)

SGT is an award-winning, nationwide service provider, offering a full spectrum of systems engineering, IT, science and program management services. Founded in 1994, and headquartered in Greenbelt, Maryland, we support a wide array of government agencies and are committed to our ICE principles—focusing on integrity, customers, and employees. SGT works closely with our customers and teammates to ensure the best possible solutions for today's most challenging problems. We hold the following certifications: ISO 9001:2008; AS9100; ISO2000; CMMI Level 3.

We are involved in a wide range of Earth and space science research ranging from studying the ice loss over ice sheets, to monitoring sea level rise, developing advanced intelligent computer systems for planetary rovers, to science data processing and dissemination. From missions exploring distant planets and asteroids, near to Earth, and circling the moon, to rovers traversing planetary surfaces and missions that provide telescopic views of the heavens, SGT's engineering and scientific expertise assist in the furtherance of human inquiry.

Our scientists study geodynamical processes to gain insight into the structure and composition of the Earth and the redistribution of mass associated with both tidal and nontidal sources of forcing. SGT, partnered with NASA Goddard Institute for Space Studies (GISS) program, is a leader in the study of climate change.

In addition to this, SGT provides end-to-end IT services for science and archival data centers, mission control centers, ground data acquisitions, campuswide network management, and numerous other areas, delivering innovative, customer-focused IT support.

We infuse and deploy advanced information systems technology into missions using numerical analysis and high-performance computing, algorithm development, modeling, GIS and web mapping, intelligent systems, agile science data processing, and archiving systems.

SGT is recognized for our successful contract performance and advantageous cost management solutions, and have received some of the industry's most prestigious awards, including NASA's prestigious George M. Low Award for Quality and Excellence.

SGT is proud to be a corporate member of the AMS! Visit us at www.sgt-inc.com.

NAVAL WEATHER SERVICE ASSOCIATION

The Naval Weather Service Association (NWSA) is an association of naval officers, enlisted men and women, and civilians who have provided meteorological, oceanographic and numerical predictions services to the United States Navy as well as all other military services. The membership consists predominately of current and former meteorological specialists (aerographers mates), meteorologists & oceanographers, computer scientists, and academics. The NWSA was formed in August 1976 in order to preserve friendships beyond active service and sustain an ongoing relationship with active duty members of the Naval Meteorological and Oceanography Command.

In 1978 the Association established a scholarship fund to support those seeking degrees in meteorology, oceanography, and atmospheric sciences and has provided annual awards for more than 30 years.

In 2011 the membership approved the transfer of management responsibilities of the "Naval Weather Service Association Scholarship" to the AMS. The AMS will safeguard and manage the funds gifted by the NWSA for the specific purpose of sustaining two annual awards based on selections of the AMS Scholarship Committee. The fund provided by the generous contributions of the NWSA membership will allow the "Naval Weather Service Association Scholarship" to be awarded for at least the next 10–15 years. For more information about the NWSA please visit the Association's website: www.navalweather.org/home.html

THE PERCIVAL D. WARK AND CLARA B. (MACKEY) WARK ENDOWED SCHOLARSHIP

The Percival D. Wark and Clara B. (Mackey) Wark Scholarship honors the late parents of Dr. David Q. Wark, a longtime AMS member. Dr. Wark, a United States federal employee for over a half-a-century, and a longtime AMS member and Fellow of AMS, has endowed an AMS Named Scholarship in honor of his parents, Percival Damon Wark and Clara Belle (Mackey) Wark. As stated by Dr. Wark, "The establishment of this scholarship is prompted by the donor's acknowledgment of the outstanding scientific and cultural leadership of the AMS, as well as its unique and universal position in promoting the science of meteorology. It is fitting that Percival D. Wark and Clara B. (Mackey) Wark should be memorialized in this milieu."

THE BERNARD VONNEGUT AND VINCENT SCHAEFER ENDOWED SCHOLARSHIP

The Bernard Vonnegut and Vincent Schaefer Scholarship honors two individuals who worked as colleagues and were friends over many years, and who made significant contributions to science and meteorology. In addition to their outstanding scientific contributions, those who knew Bernie and Vince knew of their zest for learning and discovery that carried through their entire lives, and most importantly, the positive outlook and encouragement that they conveyed to all of their students. In an effort to honor these two individuals and their contributions to the sciences, the Vonnegut/Schaefer Scholarship Fund has been established in their name. To reach the scholarship endowment level necessary, Bernie's first graduate student has pledged a two-for-one challenge match of $50,000 over the next two years. For every dollar contributed to the Vonnegut/Schaefer Freshman Scholarship, it will be matched with a two-dollar gift.

EDGAR J. SALTSMAN ENDOWED SCHOLARSHIP

The Edgar J. Saltsman Scholarship honors the late Ed Saltsman, a longtime AMS member. After graduating from high school, Mr. Saltsman continued his education at Cleveland College and Indiana University where he majored in math. Following school he enlisted in the United States Air Force and served as a climatologist and meteorologist. He earned the rank of major before retiring from service. After serving in the air force he worked with the U.S. Weather Bureau (now known as NOAA's National Weather Service) in both Washington, D.C., and in New Orleans.

2014 AMS Named Undergraduate Scholarship Recipients

AMS is pleased to announce the recipients of the 2014 AMS Named Scholarships

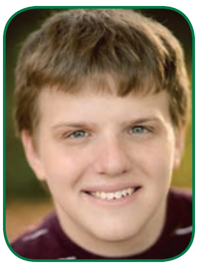
AMS Named Scholarships are established through contributions made by AMS members and friends of AMS. The scholarships are established in memory of a loved one or to honor an individual's contributions to the sciences. The scholarships are awarded to students entering their final year of undergraduate study in the atmospheric or related oceanic or hydrologic sciences. Awards are based on academic excellence and any specific award criteria, including financial need and scientific discipline that a particular scholarship has as a requirement. The stipend amounts for the scholarships vary.

AMS expresses its deep appreciation to all of the individuals and organizations that have contributed to the establishment of the following scholarships:

The Orville Family Endowed Scholarship
The Dr. Pedro Grau Undergraduate Scholarship
The Guillermo Salazar Rodriguez Undergraduate Scholarship
The Mark J. Schroeder Endowed Scholarship in Meteorology
The Richard and Helen Hagemeyer Scholarship
The Ethan and Allan Murphy Endowed Memorial Scholarship
The Werner A. Baum Endowed Scholarship
The Loren W. Crow Memorial Scholarship
The Larry R. Johnson Memorial Scholarship
The Bob Glahn Scholarship in Statistical Meteorology
The Om and Saraswati Bahethi Scholarship
The Carl W. Kreitzberg Endowed Scholarship
The David S. Johnson Endowed Scholarship
The Saraswati (Sara) Bahethi Scholarship
The Dr. Yoram Kauffman Scholarship
The Bhanwar Lal Bahethi Scholarship
The Karen Hauschild Friday Endowed Scholarship
The K. Vic Ooyama Endowed Scholarship
The Dr. Robert S. Fraser Scholarship
The Michael A. Roberts, Jr. Endowed Scholarship
The Naval Weather Service Association Scholarship
The Ken Reeves-AccuWeather Memorial Scholarship

THE ORVILLE FAMILY ENDOWED SCHOLARSHIP

Aaron L. Match has been awarded The Orville Family Endowed Scholarship in meteorology. Mr. Match is majoring in atmospheric science at Cornell University and is focusing his studies on atmospheric dynamics and climate variability.



THE DR. PEDRO GRAU UNDERGRADUATE SCHOLARSHIP

Sean W. Freeman has been awarded The Dr. Pedro Grau Undergraduate Scholarship. Mr. Freeman is majoring in meteorology at the Florida State University focusing his studies on atmospheric modeling and mesoscale meteorology.

THE GUILLERMO SALAZAR RODRIGUEZ UNDERGRADUATE SCHOLARSHIP

Justin W. Whitaker has been awarded The Guillermo Salazar Rodriguez Undergraduate Scholarship. Mr. Whitaker is majoring in physics and mathematics at Wofford College and is focusing his studies on severe weather forecasting, tropical meteorology, and climate science research.

THE MARK J. SCHROEDER ENDOWED SCHOLARSHIP IN METEOROLOGY

Shawn M. Cheeks has been awarded The Mark J. Schroeder Endowed Scholarship in Meteorology. Mr. Cheeks is majoring in computer science and applied mathematics at Marshall University where he is studying numerical modeling and mountain meteorology.

THE RICHARD AND HELEN HAGEMEYER SCHOLARSHIP

Johnathan J. Metz has been awarded The Richard and Helen Hagemeyer Scholarship. Mr. Metz is majoring in atmospheric science at the University of North Dakota focusing on numerical weather prediction (NWP), particularly in the development of new NWP models.

THE ETHAN AND ALLAN MURPHY MEMORIAL SCHOLARSHIP

Tyler Case has been awarded The Ethan and Allan Murphy Endowed Memorial Scholarship. Mr. Case is majoring in meteorology at Rutgers University where he is focusing his studies on forecasting and broadcast meteorology.

THE WERNER A. BAUM ENDOWED SCHOLARSHIP

John R. Banghoff has been awarded The Werner A. Baum Endowed Undergraduate Scholarship. Mr. Bangoff is majoring in atmospheric science at The Ohio State University where he is focusing his studies on forecasting with an interest in broadcast meteorology.

THE LOREN W. CROW MEMORIAL SCHOLARSHIP

Shawn L. Handler has been awarded The Loren W. Crow Scholarship. Mr. Handler is majoring in meteorology at Plymouth State University where he is focusing his studies on synoptic and mesoscale meteorology.

THE LARRY R. JOHNSON MEMORIAL SCHOLARSHIP

Matthew D. Flournoy has been awarded The Larry R. Johnson Memorial Scholarship. Mr. Flournoy is majoring in meteorology at the Pennsylvania State University focusing his studies on mesoscale meteorology, convective storms, and associated tornadogenesis.

THE BOB GLAHN SCHOLARSHIP IN STATISTICAL METEOROLOGY

Nathan R. Kelly has been awarded The Bob Glahn Scholarship in Statistical Meteorology. Mr. Kelly is majoring in meteorology at Valparaiso University where he is focusing his studies on data analysis and numerical modeling.

THE OM AND SARASWATI BAHETHI SCHOLARSHIP

Christopher D. McCray has been awarded The Om and Saraswati (Sara) Bahethi Scholarship. Mr. McCray is majoring in atmospheric science and mathematics at Lyndon State College where he is focusing his studies on winter weather and synoptic meteorology.

THE CARL W. KREITZBERG ENDOWED SCHOLARSHIP

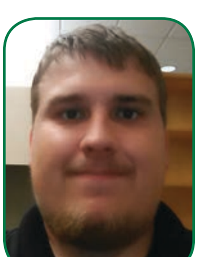
Makenzie J. Krocak has been awarded The Carl W. Kreitzberg Endowed Scholarship. Ms. Krocak is majoring in meteorology at Iowa State University and is studying severe weather prediction and communication.

THE DAVID S. JOHNSON ENDOWED SCHOLARSHIP

Samuel J. Childs has been awarded The David S. Johnson Endowed Scholarship. Mr. Childs is majoring in atmospheric science at Purdue University and is studying tornado climatology and extreme weather and climate.

THE SARASWATI (SARA) BAHETHI SCHOLARSHIP

Julie I. Barnum has been awarded The Saraswati (Sara) Bahethi Scholarship. Ms. Barnum is majoring in applied physics at Missouri State University where she is focusing her studies on radar meteorology, atmospheric electricity, cloud physics, and cloud dynamics.



THE DR. YORAM KAUFMAN SCHOLARSHIP

Montgomery L. Flora has been awarded The Dr. Yoram Kaufman Scholarship. Mr. Flora is majoring in meteorology at Ball State University where he is studying numerical and analytical solution techniques to the governing partial differential equations.

THE BHANWAR LAL BAHETHI SCHOLARSHIP

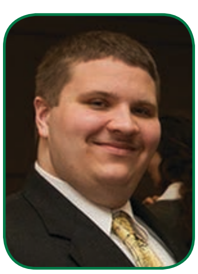
Thomas J. Sherman has been awarded The Bhanwar Lal Bahethi Scholarship. Mr. Sherman is majoring in mathematics and environmental sciences at the University of Virginia where he is studying boundary layer meteorology, mathematical atmospheric modeling, and remote sensing applications.

THE KAREN HAUSCHILD FRIDAY ENDOWED SCHOLARSHIP

Abby L. Kenyon has been awarded The Karen Hauschild Friday Scholarship. Ms. Kenyon is an undergraduate student at Valparaiso University and is majoring in meteorology and mathematics. She is focusing her studies on severe storms, tornadogenesis, synoptic-scale atmospheric dynamics, and tropical circulations.

THE K. VIC OOYAMA ENDOWED SCHOLARSHIP

Allison M. Young has been awarded The K. Vic Ooyama Endowed Scholarship. Ms. Young is majoring in meteorology at Valparaiso University where she is focusing her studies on climatology, climate change, and disaster risk management.



DR. ROBERT S. FRASER SCHOLARSHIP

Ryan J. Connelly has been awarded The Dr. Robert S. Fraser Scholarship. Mr. Connelly is majoring in meteorology at Valparaiso University and is interested in operational and applied research.

THE MICHAEL A. ROBERTS, JR. SCHOLARSHIP

Rachel L. Miller has been awarded The Michael A. Roberts, Jr. Scholarship. Ms. Miller is majoring in meteorology at the University of Oklahoma where she is focusing her studies on tornadogenesis, lightning, supercell dynamics, and mesoscale meteorology.

THE NAVAL WEATHER SERVICE ASSOCIATION (NWSA) SCHOLARSHIP

Madison R. May has been awarded The Naval Weather Service Association Scholarship. Ms. May is majoring in hydrometeorology at the University of Kansas where she is focusing on how water and carbon interact in the lower atmosphere and surface.

THE KEN REEVES ACCUWEATHER MEMORIAL SCHOLARSHIP

Katie E. Voitik has been awarded The Ken Reeves Scholarship. Ms. Voitik is majoring in meteorology at Iowa State University and is studying synoptic meteorology and forecasting.

2014 NAMED UNDERGRADUATE SCHOLARSHIP SPONSORS

The Orville Family Endowed Scholarship honors the family's more than 80 years of continuous service to meteorology. The late Howard T. Orville, head of the Naval Aerological Service, 1940–1950, had a career marked by many commendations. After his retirement from the navy, he held key industrial posts and was appointed by President Eisenhower as chairman of the Advisory Committee on Weather Control in 1953. Capt. Orville was president of the AMS, 1948–1949. The scholarship also honors his sons, the late Harold D. Orville, distinguished professor of meteorology, South Dakota Institute of Mines and Technology, and Richard E. Orville, professor of atmospheric sciences, Texas A&M University. Harold Orville performed pioneering research in a career centered on numerical cloud modeling and served the Society as Councilor, Executive Committee member, Commissioner, and journal editor. Richard Orville performed groundbreaking research in lightning science, including development of the National Lightning Detection Network and served the Society as Publications Commissioner, Education Commissioner, and as a consequence, was a Council member for twelve years. Through a bequest from the estate of Howard T. Orville and contributions from members of his family, the endowed undergraduate scholarship in the amount of $5,000 is awarded annually.

The Dr. Pedro Grau Undergraduate Scholarship honors the late Dr. Pedro Grau y Triana. Medical doctor, legislator, original inventor, and businessman, Dr. Grau was a hardworking, globe-trotting researcher of human nature and historic events. Among his many interests were tropical hurricanes. Having gone through several very severe ones, he thought that every effort should be made to understand their nature and improve the forecasting. The scholarship is given by his daughter, Mrs. Manon Rodriguez. Mrs. Rodriguez is also generously supporting **The Guillermo Salazar Rodriguez Undergraduate Scholarship**, in honor of her late husband. Mrs. Rodriguez has funded a $2,500 scholarship in each of the above names in the interest of seeing more effort and resources devoted to atmospheric research.

The Mark J. Schroeder Endowed Scholarship in Meteorology is funded by Mark and Eve Schroeder. Schroeder, former research meteorologist of the U.S. Forest Service and the National Weather Service, could be considered one of the pioneers of fire meteorology. For over a quarter of a century, he literally worked on every facet of the fire meteorology program. After nearly 16 years on assignment to the U.S. Forest Service, he transferred to that agency in 1971. During World War II he served in the American and European theaters as a weather reconnaissance officer. In 1973 he retired from the U.S. Air Force Reserve as a lieutenant colonel. The endowed undergraduate scholarship in the amount of $5,000 is awarded annually.

The Richard and Helen Hagemeyer Scholarship honors Richard and Helen Hagemeyer. Prior to Mr. Hagemeyer's death in 2001, he and Mrs. Hagemeyer had served the weather industry by working at the National Oceanic and Atmospheric Administration and its predecessor agencies for more than 75 years. Mrs. Hagemeyer retired from the Weather Bureau in 1978. Mr. Hagemeyer served as the director of the Pacific Region of the National Weather Service. They have funded a $3,000 undergraduate scholarship to help fulfill a desire to support atmospheric and related oceanic sciences education.

The Ethan and Allan Murphy Memorial Scholarship honors the late Ethan and Allan Murphy, father and son, who each made a number of contributions to the field of meteorology throughout their individual careers. To honor these contributions and the memories of these two men, the family of Ethan and Allan Murphy has established a scholarship that will be augmented by contributions from interested individuals. The scholarship supports an undergraduate student who, through curricular or extracurricular activities, has evidenced an interest in weather forecasting or in the value and utilization of forecasts. The scholarship carries a $2,000 stipend

The Werner A. Baum Endowed Scholarship honors the late Prof. Werner A. Baum, a national and international leader in meteorology. Prof. Baum was a strong advocate of the highest standards for education and research and promoted those standards through administrative positions in universities and the government. The endowed undergraduate scholarship in the amount of $5,000 is awarded annually.

The Loren W. Crow Memorial Scholarship is sponsored by NCIM, an association of private sector meteorologists, of which Loren Crow was a founder and charter member. As a mentor and friend of many of today's practitioners of applied meteorology, Loren Crow shall be remembered as a principal leader in the field of applied meteorology. He envisaged and advocated vigorous expansion of private sector consulting. He believed that innovation by a few or even by one can have great future influence. His contributions during a career of a half-century can be found in present practices, and his concerns for the field as a whole have withstood the test of time. The scholarship carries a $2,000 stipend and is awarded to a student that has evidenced an interest in applied meteorology.

Founded in 1968, the NCIM's mission is to promote the ethical, scientifically rigorous, and prosperous practice of meteorology to serve the broad range of customers in the public and private sectors throughout the world. All NCIM members are Certified Consulting Meteorologists (CCM), and for more than three decades, NCIM has conducted far-ranging activities for professional development through mentoring, networking, marketing, advocacy, workshops, scholarships, and internships.

The Larry R. Johnson Memorial Scholarship honors the late Larry Johnson whose contributions to meteorology spanned over 30 years and careers with the U.S. Air Force and PRC [now known as Northrop Grumman Information Technology (IT)]. Larry served 10 years with PRC in a variety of assignments on the Advanced Weather Interactive Processing System (AWIPS) program, the integrating element of the $4.5B National Weather Service Modernization. Known as "Mr. AWIPS," Larry's tenure on AWIPS was longer than any other person, and his contributions to the success of AWIPS stand out among all others. The scholarship carries a $2,000 stipend.

The Bob Glahn Scholarship in Statistical Meteorology is funded by Bob Glahn, who, for nearly half a century, has been involved in pioneering work in the development of statistical applications within the atmospheric sciences. As one in a long list of achievements, Dr. Glahn developed the concept of Model Output Statistics (MOS) used by many countries worldwide. The scholarship carries a $2,500 stipend.

The Om and Saraswati Bahethi Scholarship is sponsored by Science Systems and Applications, Inc. (SSAI), a Lanham, Maryland–based company. Om and Sara Bahethi, both originally from India, are naturalized United States citizens and the founders of SSAI. Om would not have completed his college education and doctoral degree in physics in the United States had it not been for scholarships and assistance provided by various government and educational institutions. SSAI is very proud of Om and Sara's strong commitment to assisting students pursuing degrees in the atmospheric and related sciences. SSAI, a woman-owned small business, has been performing scientific and technological applications services and has steadily grown since its incorporation in April 1977. SSAI has received numerous commendations for within-budget and on-time quality support services. SSAI's areas of expertise are Earth and space sciences, advanced computing, scientific analysis, instruments engineering, systems development, and information technology. The scholarship carries a $2,000 stipend.

2014 NAMED UNDERGRADUATE SCHOLARSHIP SPONSORS

The Carl W. Kreitzberg Endowed Scholarship honors the late Dr. Kreitzberg's role as a scientist, mentor, colleague, and friend. Throughout his career he was a dedicated leader and advocate for observational data campaigns and numerical modeling research to better understand mesoscale weather phenomenon. He inspired his students with his innate curiosity and constant questioning, instilling in many of them a similar drive. Dr. Kreitzberg always believed that research in the search of understanding was a fun, enjoyable activity. He demonstrated this by his intensely curious spirit in the classroom each and every day. He also imparted this to his one-on-one mentoring with graduate students. The scholarship carries a $2,000 stipend.

The David S. Johnson Endowed Scholarship was established in memory of David Simonds Johnson, past president and Fellow of AMS and a pioneer in the use of weather satellites. Johnson, "Dave" to friends and associates alike, was a meteorologist and administrator for NOAA for more than a half-century and served as the first assistant administrator of the National Environmental Satellite, Data and Information Service (NESDIS). The scholarship carries a $3,000 stipend.

The Saraswati (Sara) Bahethi Scholarship is sponsored by Science Systems and Applications, Inc. (SSAI), a woman-owned small business, that has been performing scientific and technological applications services for NASA, NOAA, and other federal agencies since its incorporation in 1977. SSAI's areas of expertise are Earth and space sciences, advanced computing, complex science data and information systems, scientific analysis, instrument engineering, systems development, and information technology. SSAI is also a proud sponsor of the AMS/Om and Saraswati Bahethi Scholarship, which is named after the founders of SSAI, and is awarded to students entering their final year of undergraduate study. The scholarship carries a $2,000 stipend.

The Dr. Yoram Kaufman Scholarship has been established by Science Systems and Applications, Inc. (SSAI), in memory of Dr. Yoram Kaufman. Dr. Kaufman was a leading scientist at NASA's Goddard Space Flight Center (GSFC) whose research led to greater understanding of global warming. His primary fields were meteorology and climate change, with a specialty in analyzing aerosols—airborne solid and liquid particles in the atmosphere. He wrote more than 200 scientific papers, found ways to measure aerosols to determine whether they were caused by humans or occurred naturally, and was working to understand their ultimate effect on Earth's warming climate. In addition to being a compassionate and charismatic leader, Dr. Kaufman was also an excellent motivator who provided opportunities to SSAI. The scholarship carries a $2,000 stipend.

The Bhanwar Lal Bahethi Scholarship has been established and sponsored by Dr. Om P. Bahethi in memory of his beloved elder brother to honor his generosity in assisting and motivating numerous youngsters to seek an education in science and engineering. Bhanwar Bahethi (1930–1972) did not receive a formal education. Because of his interests in science, mechanics, and how things work, however, he was able to teach himself car repair skills that allowed him to become an auto mechanic and operate a small roadside, open-air garage in the desert city of Jodhpur, India. Numerous students and families benefited from Bhanwar's assistance. It was his generosity in supporting his younger brother's education and travel to the United States that enabled Om to receive a Ph.D. in physics and to start a company, Science Systems and Applications, Inc. (SSAI). SSAI excels in science and technology support services. The scholarship carries a $2,000 stipend.

The Karen Hauschild Friday Endowed Scholarship has been established by the family of Karen Hauschild Friday to honor her life. Karen Hauschild Friday was born December 3, 1940 in Fairview, Oklahoma. The dust bowl was particularly severe in northwestern Oklahoma, and upon failure of the family farm, Karen's father moved to work at Tinker Air Force Base in the Douglas Aircraft plant in support of the war effort. She married Dr. Elbert W. (Joe) Friday in 1959. She was a supportive wife during Joe's 20-year career in the air force, during his terms as deputy director and director of the National Weather Service, and during the rest of their 47-and-a-half-year marriage. She was a wonderful mother for their two daughters and a devoted grandmother taking joy with her five grandchildren. Joe and Karen traveled extensively throughout the American west where Karen enjoyed her love of American Indian art and culture. She lost a two-and-a-half-year battle with cancer on March 21, 2007. The scholarship carries a $2,500 stipend.

The K. Vic Ooyama Endowed Scholarship honors the late Katsuyuki Ooyama, whose distinguished science career spanned more than 50 years. Dr. Ooyama was known for his valuable contributions in advancing the theory and modeling of tropical cyclones, for his many years of service to NOAA, and for influencing an entire younger generation of scientists studying cyclogenesis. The scholarship carries a $2,500 stipend.

Dr. Robert S. Fraser Scholarship has been established by Science Systems and Applications, Inc. (SSAI) in honor Dr. Robert (Bob) S. Fraser, a mentor to Om Bahethi, president of SSAI. While working at the NASA/GSFC Laboratory for Atmospheres for almost 22 years, Bob took a great interest as a mentor to many professionals working in the areas of satellite remote sensing and modeling of transfer of solar radiation in the Earth's atmosphere. Bob spent innumerable hours with Om, teaching him the complexities of modeling the physics, atmospheric processes, and numerical schemes that are the heart and soul of computing radiation transfer. Bob, in more ways than one, communicated a positive outlook on life, humility, and sincerity when Om worked as a Goddard contractor. Bob's generous assistance and wisdom contributed to outstanding learning and the career advancement of everyone who came in contact with him. SSAI is very proud of Dr. Robert Fraser's strong commitment to assisting others in their careers. The scholarship carries a $2,000 stipend.

The Michael A. Roberts, Jr. Scholarship has been established by family and friends to honor his memory and contributions to the sciences. Mr. Roberts was an active member of AMS and had a distinguished record serving his country as a lieutenant in Vietnam in the U.S. Air Force Strategic Air Command Center. He was an accomplished scholar who earned several degrees and professionally worked at Enron, leading a research team designing systems to capture timely meteorological data. He then joined The Citidal Group where he led a team focusing on the impacts of weather on natural gas and electric power supply and demand and on the pricing of these and other commodities. The scholarship carries a $2,000 stipend.

The Naval Weather Service Association (NWSA) Scholarship. The NWSA is an association of naval officers, enlisted men and women, and civilians who have provided meteorological, oceanographic, and numerical predictions services to the United States Navy as well as all other military services. The membership consists predominately of current and former meteorological specialists (aerographers mates), meteorologists & oceanographers, computer scientists, and academics. The NWSA was formed in August 1976 in order to preserve friendships beyond active service and sustain an ongoing relationship with active duty members of the Naval Meteorological and Oceanography Command. The scholarship carries a $5,000 stipend.

The Ken Reeves AccuWeather Memorial Scholarship honors the late Kenneth W. Reeves and his many contributions as an advocate, mentor, and supporter of undergraduate students and their future careers in atmospheric sciences. Ken's passion for the weather led him to a successful 29-year career at AccuWeather where he served as the vice president of forecast operations. Ken would actively recruit, teach, and guide recently graduated meteorology and atmospheric science students as they began their careers. The scholarship assists outstanding students pursuing undergraduate degrees in the atmospheric sciences looking to apply their skills to operational meteorology, as Ken did throughout his rich and successful career. The scholarship is awarded annually in the amount of $3,000.

CALENDAR OF MEETINGS

The Call for Papers and Calendar sections list conferences, symposia, and workshops that are of potential interest to AMS members. **Complete information about events listed in the calendar can be found on the meetings page of the AMS website, www.ametsoc.org. New additions to the calendar are highlighted.**

To list an event in the calendar, please submit the event name, dates, location, and deadlines for abstracts, manuscripts, and preregistration to amsmtgs@ametsoc.org. For a submission to appear in a given issue, it must be submitted at least eight weeks prior to the month of publication (that is, to appear in the March *Bulletin,* the submission must be received by 1 January).

AMS MEETINGS

2014

OCTOBER

19th Biennial Joint AMS/AGU Heads and Chairs Meeting: Best Practices: Meeting the Challenges Facing Academic Geoscience Programs, 16–17 October, Boulder, Colorado

NOVEMBER

27th Conference on Severe Local Storms, 3–7 November, Madison, Wisconsin
Abstract deadline: 1 July 2014
Preregistration deadline: 9 September 2014
Manuscript deadline: 7 December 2014
Initial announcement published: Feb. 2014

2015

JANUARY

AMS Short Course: A Beginner's Course to Using Python in Climate and Meteorology, 3–4 January, Phoenix, Arizona
Preregistration deadline: 1 December 2014
Initial announcement published: Aug. 2014

AMS 2015 Annual Meeting Presidential Forum–Will Weather Change Forever: Anticipating Meteorology in 2040, 5 January, Phoenix, Arizona
Preregistration deadline: 1 December 2014
Initial announcement published: Sept. 2014

Harry R. Glahn Symposium: The Evolution of Post-processing Methods in Weather Forecasting and Analysis, 6 January, Phoenix, Arizona
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: June 2014

Eugenia Kalnay Symposium, 7 January, Phoenix, Arizona
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: May 2014

***14th Annual AMS Student Conference, 3–4 January, Phoenix, Arizona**

Third Annual AMS Conference for Early Career Professionals, 4 January, Phoenix, Arizona
Preregistration deadline: 16 December 2014
Initial announcement published: June 2014

***31st Conference on Environmental Information Processing Technologies, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***29th Conference on Hydrology, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***27th Conference on Climate Variability and Change, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***24th Symposium on Education, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: April 2014

***20th Conference on Planned and Inadvertent Weather Modification, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: May 2014

***20th Conference on Satellite Meteorology and Oceanography, 11th Symposium on New Generation Operational Environmental Satellite Systems, and Third AMS Symposium on the Joint Center for Satellite Data Assimilation (JCSDA), 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

*An exhibit program will be held at this meeting.

***19th Conference on Air–Sea Interaction, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***19th Conference on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS), 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***18th Conference on the Middle Atmosphere, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***18th Conference of Atmospheric Science Librarians International, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Initial announcement published: July 2014

***17th Conference on Conference on Atmospheric Chemistry, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***17th Conference on Aviation, Range and Aerospace Meteorology (ARAM), 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***13th Conference on Artificial and Computational Intelligence and its Applications to the Environmental Sciences, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***13th History Symposium, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: July 2014

***13th Symposium on the Coastal Environment, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***12th Conference on Space Weather, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***11IMPACTS: Major Weather Events and Societal Impacts of 2014, 6 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Tenth Symposium on Societal Applications: Policy, Research and Practice, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Eighth Annual CCM Forum, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: July 2014

***Seventh Symposium on Lidar Atmospheric Applications, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Seventh Symposium on Aerosol–Cloud–Climate Interactions, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Seventh Conference on the Meteorological Applications of Lightning Data, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Sixth Conference on Environment and Health, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Sixth Conference on Weather, Climate, and the New Energy Economy, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: May 2014

***Fifth Conference on Transition of Research to Operations, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Fifth Symposium on Advances in Modeling and Analysis Using Python, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

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* An exhibit program will be held at this meeting.

***Third Annual Symposium on the Weather and Climate Enterprise, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Third Symposium on Building a Weather-Ready Nation: Enhancing Our Nation's Readiness, Responsiveness, and Resilience to High Impact Weather Events, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Third Symposium on Prediction of the Madden–Julian Oscillation: Processes, Prediction, and Impact, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: April 2014

First Symposium on High Performance Computing for Weather, Water, and Climate, 8 January, Phoenix, Arizona
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: April 2014

***Special Symposium on Model Postprocessing and Downscaling, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Mar. 2014

***Air Pollution Meteorology and Human Health Symposium, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: July 2014

***Special Session on the South Asia Monsoon, 4–8 January, Phoenix, Arizona**
Abstract deadline: 1 August 2014
Preregistration deadline: 1 December 2014
Manuscript deadline: 5 February 2015
Initial announcement published: Aug. 2014

MAY

11th Symposium on Fire and Forest Meteorology, 5–7 May, Minneapolis, Minnesota
Abstract deadline: 12 January 2015
Preregistration deadline: 24 March 2015
Manuscript Deadline: 4 June 2015
Initial announcement published: Sept. 2014

AUGUST

16th Conference on Mesoscale Processes, 3–6 August, Boston, Massachusetts
Abstract deadline: 6 April 2015
Preregistration deadline: 22 June 2015
Manuscript Deadline: 4 September 2015
Initial announcement published: Sept. 2014

MEETINGS OF INTEREST

2014

SEPTEMBER

Eighth European Conference on Radar in Meteorology and Hydrology, 1–5 September, Garmisch-Partenkirchen, Germany

20th International Congress of Biometeorology, 28 September–2 October, Cleveland, Ohio

OCTOBER

14th Annual Meeting of the European Meteorological Society (EMS) and the 10th European Conference on Applied Climatology (ECAC), 6–10 October, Prague, Czech Republic

Climate Research and Earth Observations from Space: Climate Information for Decision Making, 13–17 October, Darmstadt, Germany

Fifth Tri-State Weather Conference, 18 October, Danbury, Connecticut

2014 GSA Annual Meeting, 19–22 October, Vancouver, British Columbia, Canada

NOAA's 39th Climate Diagnostics and Prediction Workshop, 20–23 October, St. Louis, Missouri

Women in STEM Idea Exchange Summit, 21 October, Waltham, Massachusetts

2015

MAY

ASABE First Climate Change Symposium: Adaptation and Mitigation, 3–5 May, Chicago, Illinois

JUNE

Workshop on Meteorological Sensitivity Analysis and Data Assimilation, 1–5 June, Roanoke, West Virginia

* An exhibit program will be held at this meeting.

ANNOUNCEMENT

AMS 2015 Annual Meeting Presidential Forum–Will Weather Change Forever: Anticipating Meteorology in 2040, 5 January 2015, Phoenix, Arizona

Twenty five years hence, meteorology will be much different. Personal sensors will monitor weather nearly everywhere. Advanced computing will allow us to forecast at perhaps minute scales and kilometer resolutions, customized for each particular user. Post-mobile devices will enable instantaneous use of the information—even in remote areas of today's developing nations. Transportation will be safer, businesses will operate more efficiently, events will automatically schedule around anticipated weather, and much more. Many aspects of our daily lives will change forever. Climate change's possibilities add a critical dimension. Should global weather patterns be altered, forecasting could become more challenging than today.

Anticipating the future is as much art as science. But this future is now being built—through the groundwork laid by those now near the end of their careers, by today's young professionals who will become 2040's retirees, and by current students who will be our profession's leaders. The Forum will explore a variety of topics:

- Where will advances in the science and technology take us?
- Will our lives be better, safer, and healthier?
- Will the changes advance developing world prosperity and help the global economy?
- What new uses will people find for weather information?
- Will climate change alter global weather patterns? How will all environmental forecasting change?
- Could actions such as geoengineering create additional challenges for meteorologists?
- What role will meteorologists play in twenty-five years?

Three speakers will represent the key demographic groups for whom meteorology in 2040 will be important:

- A well-known futurist or technology visionary from outside the field
- An early career professional
- A student

Each will present their vision for 2040 followed by a roundtable discussion among the three presenters moderated by a student or early career professional.

For additional information, please contact Bill Gail (e-mail: bgail@globalweathercorp.com). (9/14)

CALL FOR PAPERS

11th Symposium on Fire and Forest Meteorology, 5–7 May 2015, Minneapolis, Minnesota

The 11th Symposium on Fire and Forest Meteorology, sponsored by the American Meteorological Society and organized by the AMS Committee on Agricultural and Forest Meteorology, will be held 5–7 May 2015 at the Crowne Plaza Minneapolis Northstar Hotel, Minneapolis, Minnesota (www.cpminneapolis.com/).

The theme of the symposium will be to share experiences, new techniques and technologies, and/or changes in the areas of but not limited to (1) utilization of weather and climate information in relation to wildland fire; (2) operational forecasting (short- to long-term) of fire weather; (3) model studies and development, including theoretical models, coupled fire–atmosphere models, and mesoscale models; (4) use and assessment of meteorological information in fire management planning; (5) decision support tool development; (6) smoke modeling, management, and mitigation; (7) improvements to fire danger and fire behavior systems that utilize meteorology; and (8) field studies of fire–atmosphere interactions.

Please submit your abstract electronically via the web by *12 January 2015* (refer to the AMS web page at www.ametsoc.org for instructions). An abstract fee of $95 (payable by credit card or purchase order) is charged at the time of submission (refundable only if the abstract is not accepted). Authors of accepted presentations will be notified (via e-mail) by the end of February. Authors of invited and accepted papers will still be asked to contribute to the web-based proceedings of the conference by submitting an extended abstract. Instructions for formatting extended abstracts will be posted on the AMS conference website. Extended abstracts (file size up to 10 MB) must be submitted electronically by *4 June 2015*. All abstracts, extended abstracts, and presentations will be made available on the AMS website.

For further program information contact either one of the Program cochairpersons: Tim Brown, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512-1095 (tel: 775-674-7090; fax: 775-674-7016; e-mail: tbrown@dri.edu) or Brian Potter, Forestry Sciences Lab, 400 N 34th St., Suite 201, Seattle, WA 98103 (tel: 206-732-7828; fax: 206-732-7801; e-mail: bpotter@fs.fed.us). (9/14)

ANNOUNCEMENT

Workshop on Meteorological Sensitivity Analysis and Data Assimilation, 1–5 June 2015, Roanoke, West Virginia

The Workshop on Meteorological Sensitivity Analysis and Data Assimilation, cosponsored by Morgan State University, Baltimore, Maryland; the U.S. National Science Foundation; and the Global Modeling and Assimilation Office at NASA Goddard Space Flight Center, will be held 1–5 June 2015 at the Stonewall Resort in Roanoke, West Virginia. This is the 10th in the series of "Adjoint Workshops" that began in 1992. It is intended to provide public evaluation of new works, reviews of techniques, and tutorials on fundamentals. Historically, more than half of each workshop has been devoted to data assimilation issues. Presentations from oceanography, geosciences, or engineering are welcome as are applications of techniques that do not include adjoint models but concern the applications to which they may otherwise apply. Opportunities for oral and poster presentations will be available. Unlike at larger meetings, all presenters will be instructed to "teach us something that you have learned" rather than to "advertise to us what you have done." The audience will be provided ample time and encouragement to critique and discuss all presentations. Further information and a call for abstracts will be posted to the workshop website (http://gmao.gsfc.nasa.gov/events/adjoint_workshop-10/) and e-mailed to interested persons in the fall of 2014.

Funds will be available for a limited number of students and postdocs to provide partial travel support (primarily the local expenses). A brief set of preworkshop tutorials describing some fundamentals not generally presented elsewhere will be offered on 31 May to help novices in the field to spin up their understanding. Workshop-supported students and postdocs will be expected to attend these tutorials. If you are a student or postdoc requesting travel support from the workshop, please contact the workshop chair by 15 December 2014 and include the name of your institution, (expected) degree date, and topic of study.

For additional information or to receive future e-mails regarding the workshop, please contact the workshop chair, Dr. Ronald Errico (e-mail: ronald.m.errico@nasa.gov, tel: 301-614-6402) or visit the conference website at http://gmao.gsfc.nasa.gov/events/adjoint_workshop-10/. (9/14)

CALL FOR PAPERS

16th Conference on Mesoscale Processes, 3–6 August 2015, Boston, Massachusetts

The 16th Conference on Mesoscale Processes, sponsored by the American Meteorological Society and organized by the AMS Committee on Mesoscale Processes, will be held 3–6 August 2015 at the Sheraton Boston Hotel in Boston, Massachusetts. A preliminary program, along with hotel and registration information, will be posted on the AMS website (www.ametsoc.org) by mid-May 2015.

The program committee seeks contributions from all areas of mesoscale meteorology, including observational, theoretical and modeling studies of mesoscale processes (e.g., gravity waves, mesoscale convective systems, mechanically forced flows, tornadoes, orographic precipitation, structure and evolution of tropical cyclones, extratropical systems). We also invite submissions treating high-impact mesoscale events as well as microphysics and aerosols, results from recent testbeds/field experiments (e.g., OWLeS, DEEPWAVE, MPEX, PECAN, …), mesoscale predictability, and mesoscale data assimilation.

The Mesoscale Processes Committee encourages abstract submissions from students for which awards will be given to the best student oral and poster presentations at the conference. Students need to indicate their willingness to be considered for these awards when submitting their abstract by selecting yes to be entered into the competition (this question appears after answering if presented by a student question). The Mesoscale Processes Committee is also offering two student travel awards to help supplement travel expenses. The award is to be used for travel expenses to and from the conference and/or lodging in Boston. To be eligible for a travel award, students must be current AMS student members and have submitted an abstract for presentation at the meeting. Furthermore, the awardees may not receive any concurrent travel support from the AMS (e.g., an AMS travel grant). The selected students will be required to pay for all costs up-front and will be reimbursed by AMS following the conference with proper receipts of approved expenses. To apply please send your CV and a brief (1/2 page) justification to the program chairpersons (contact information located below) by the abstract deadline of *6 April 2015*.

AMS policy limits participants to one oral presentation each (you may submit more than one abstract but please note any additional accepted submission will be assigned as a poster). Please submit abstracts via http://ams.confex.com/ams/ no later than *6 April 2015*. A fee of $95.00 (payable by credit card or purchase order) will be charged at the time of submission of each abstract (refundable only if abstract is not accepted). When submitting your abstract, you can indicate whether you prefer a poster or an oral presentation. The availability of oral presentations, however, will depend on the number of submissions.

Authors of accepted presentations will be notified via e-mail by mid-May 2015. Instructions for formatting extended abstracts will be posted on the AMS website. These extended abstracts (file size up to 10 MB) must be submitted electronically by *4 September 2015*. All abstracts, extended abstracts, and presentations (including the recordings of those who granted permission) will be made available on the AMS website.

For additional information, please contact the program chairpersons: Susan C. van den Heever, Colorado State University (tel: 970-491-8501; fax: 970-491-8483; e-mail: sue@atmos.colostate.edu) or Zhiyong (Ellie) Meng, Peking University (tel: +86-10-62751131; fax: +86-10-6751094; e-mail: zymeng@pku.edu.cn) (9/14)

NOMINATION SUBMISSIONS

The Council of the American Meteorological Society invites members of the AMS to submit nominations for the Society Awards, Lecturers, Named Symposia, Fellows, Honorary members, and nominees for elective Officers and Councilors of the Society.

Information regarding awards, including award descriptions, listings of previous recipients, and the process for submitting nominations are on the AMS website www.ametsoc.org/awards.

Note: Deadlines differ and some nominations must be submitted on a specific form vs. electronic submission which is available on the AMS website or by request from Headquarters.

2015 AWARDS COMMITTEES

Each committee or commission listed below has the responsibility to select and submit to the Council the names of individuals nominated for the Society's awards listed. The name(s) of individual(s) nominated, a two-page cv, a bibliography of no more than three pages, and three supporting letters should be electronically submitted before **1 May 2015** for the awards that follow, unless stated otherwise. The nominees for awards remain on the committee's active list for three years.

ATMOSPHERIC RESEARCH AWARDS COMMITTEE

The Carl-Gustaf Rossby Research Medal
The Jule G. Charney Award
The Verner E. Suomi Award*
The Remote Sensing Prize (biennial)
The Clarence Leroy Meisinger Award
The Henry G. Houghton Award

OCEANOGRAPHIC RESEARCH AWARDS COMMITTEE

The Sverdrup Gold Medal
The Henry Stommel Research Award
The Verner E. Suomi Award*
The Nicholas P. Fofonoff Award

AWARDS OVERSIGHT COMMITTEE

The Charles Franklin Brooks Award for Outstanding Services to the Society
The Cleveland Abbe Award for Distinguished Service to the Atmospheric Sciences by an Individual
The Joanne Simpson Mentorship Award
The Award for Outstanding Services to Meteorology by a Corporation
Special Awards

EDUCATION AND HUMAN RESOURCES COMMISSION

The Louis J. Battan Author's Award (Adult and K–12)
The Charles E. Anderson Award
The Teaching Excellence Award
Distinguished Science Journalism in the Atmospheric and Related Sciences

PROFESSIONAL AFFAIRS COMMISSION

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WEATHER AND CLIMATE ENTERPRISE COMMISSION

The Kenneth C. Spengler Award

LOCAL CHAPTER AFFAIRS COMMITTEE

Local Chapter of the Year Award
(nomination form available online at www.ametsoc.org/amschaps/index.html.)

* Recommended by the Atmospheric Research Awards Committee in even-numbered years and by the Oceanographic Research Awards Committee in odd-numbered years.

2015 AWARDS COMMITTEES

SCIENTIFIC AND TECHNOLOGICAL ACTIVITIES COMMISSION

The Charles L. Mitchell Award
The Award for Exceptional Specific Prediction
The Francis W. Reichelderfer Award
The Helmut E. Landsberg Award
The Award for Outstanding Achievement in Biometeorology

- **LECTURERS** *(Deadline: 1 October 2014)*
  Robert E. Horton Lecturer in Hydrology
  Bernhard Haurwitz Memorial Lecturer
  Walter Orr Roberts Lecturer

- **PAPER**
  Banner I. Miller

- **STUDENT PAPERS**
  Robert Leviton Student Prize
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- **NAMED SYMPOSIA**
  Section E, of the Policy, Guidelines, and Procedures for Awards and Lectureships provides the Policy on Named Conferences/Symposia and Special Issues of AMS Journals *(full policy description available at www.ametsoc.org/awards):*

> Recognition of scientists in the fields served by the AMS, living or deceased, in the form of a named conference or symposium or a named special issue of one of the Society's journals is an honor reserved for only the most outstanding of our colleagues. It should be awarded only to those individuals who are completing a career, or who have recently died having completed a career, of significant achievements in their field and whose contributions would make them worthy of consideration for Honorary Member of the AMS…

2015 FELLOWS COMMITTEE

The Committee's function is to submit to the Council the names of individuals for election to Fellow.

> Article III, Section 6, of the AMS Constitution provides that those eligible for election to Fellow shall have made outstanding contributions to the atmospheric or related oceanic or hydrologic sciences or their applications during a substantial period of years. The nominees for Fellow must be a member of the Society and remain on the committee's active list for three years.

A nomination letter and three supporting letters should be electronically submitted before 1 May 2015. A list of Fellows and the process for submitting nominations are on the AMS website (www.ametsoc.org/awards).

2015 NOMINATING COMMITTEE

The Committee's function is to submit to the Council the names of individuals for 1) the office of President-Elect for a term of one-year starting at the close of the 96th Annual Meeting (January 2016) and 2) four positions on the Council for a term of three-years starting at the close of the Annual Meeting. Nominations must be submitted prior to 1 April 2015 to the Nominating Committee.

HONORARY MEMBERS

Article III, Section 5, of the AMS Constitution provides that Honorary Members shall be persons of acknowledged preeminence in the atmospheric or related oceanic or hydrologic sciences, either through their own contributions to the sciences or their application or through furtherance of the advance of those sciences in some other way. They shall be exempt from all dues and assessments. The nominees for Honorary member remain on an active list for three years.

Deadline: 1 June 2015; a form and list of Honorary Members is available at www.ametsoc.org/awards.

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Bulletin of the American Meteorological Society			July 2014	
15. **Extent and Nature of Circulation**			**Average No. Copies Each Issue During Preceding 12 Months**	**No. Copies of Single Issue Published Nearest to Filing Date**
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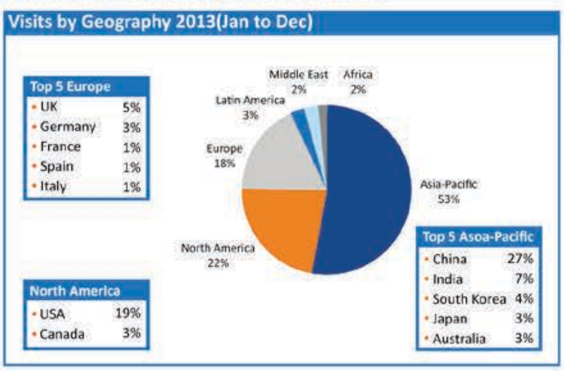

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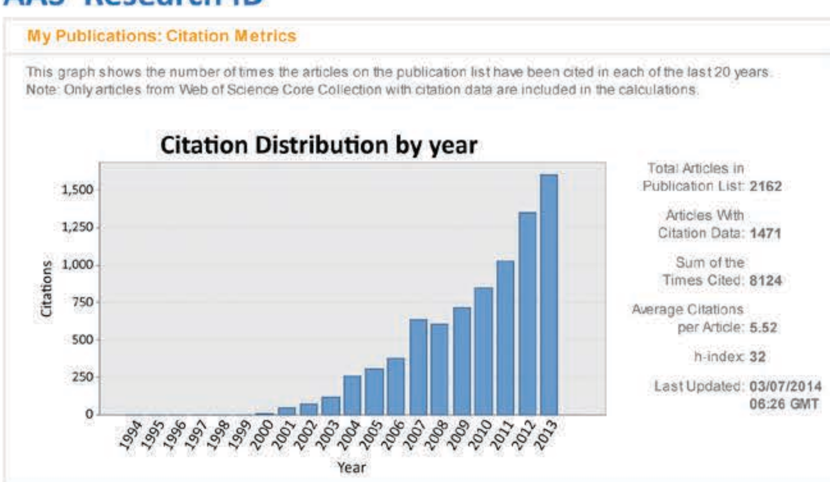

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