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ON THE COVER
For many decades our view from geostationary orbit was limited to single-band, grayscale imagery. Miller et al. (p. 1803) highlight the new, vivid color Earth information. (image: Steven Miller and Maureen Murray, Colorado State University/CIRA)

Supplements (>) and online content are available online at http://journals.ametsoc.org/toc/bams/97/10
Decaying cumulonimbus cloud photographed 2 September 2014 over Manaus, Brazil, during the ACRIDICON–CHUVA campaign. [see Wendisch et al., p. 1885; photo courtesy Steffen Gemsa, Deutsches Zentrum für Luft- und Raumfahrt (DLR)].
CoCoRaHS
A volunteer rain-measuring network takes Citizen Science to new levels, in Reges et al. (p. 1831)

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SEND US YOUR THOUGHTS

We encourage readers to write to us with comments on what they read (or would like to read) in BAMS, as well as comments on AMS events and initiatives, or simply thoughts about what’s happening in the world of atmospheric, oceanographic, hydrologic, and related sciences. When writing via e-mail, please send your messages to letterstotheeditor@ametsoc.org, or write to Letters to the Editor/BAMS, American Meteorological Society, 45 Beacon St., Boston, MA 02108. Your submissions will be considered for the “Letters to the Editor” column of BAMS.
LETTER FROM THE EDITOR:
SEEKING CHEMISTRY

How do you know when someone has changed the world? Here’s an example of how: Through satire and metaphor, the cartoonist Rube Goldberg identified a truth—our excessive reliance on technology—and transformed it into a cautionary principle. Now people see the ridiculousness of overdesigned technology and say, “Rube Goldberg.” His name has become the word for the phenomenon. That’s how you know.

Like Rube Goldberg, science has the ability to identify truths and then subvert or transform our understanding of the world. Think of the first time you looked up at the clouds and understood that these mysterious shapes in the sky do not just give us rain, but are themselves made of water and ice. Once you knew what they were, you couldn’t look at clouds the same way again.

Chemistry is the science that above all seeks to identify the world around us with unvarnished accuracy. It asks the basic question, “What is this?” Looking up at the clouds, after reading Slater et al. (p. 1797), would you see only water? At this point, you will almost certainly look at clouds and think, not just of water but also of the potassium-laden feldspar from Saharan dust and of other ice nuclei. Read Wendisch et al. (p. 1885) and look up again and wonder what part anthropogenic aerosols and trace gases play in cloud development. The towering convection of the Amazon region is not a story of moisture, pure and simple, but of a complicated chemistry.

The alchemy of science—its ability to transform understanding—is shared by all the disciplines. Chemistry, in particular, also remains inextricably linked with the processes that transform nature. Through ice nuclei, clouds can become something other than liquid. There are also other kinds of changes in this issue. It is inspiring, for example, to see the evolution of the CoCoRaHS program over the years (p. 1831) as it has grown from a regional to a national precipitation observing network.

By expanding its scope, CocoRaHS created a synergy of professional and citizen scientists, helping the network become a vehicle for meteorology, hydrology, and climate education. Look through this issue and you will find many instances where synergies are encouraged, predicted, and demanded. Perhaps the most obvious case stirs together oceanic and atmospheric science and observing and modeling to comprehend the Indian Ocean monsoon (Wijesekera et al., p. 1859). Likewise, Vaidyanathan et al. (p. 1817) see extreme heat alerts as the catalyst for combining health care and atmospheric sciences. And Andrade-Flores et al. (p. 1929) seek to improve international cooperation in the atmospheric chemistry community of Latin America to deal with the effect of that feldspar arriving from the Sahara as well as other regional issues.

Indeed the future of AMS sciences will depend on revealing the essence of things and precipitating changes—perhaps even changing the world in unknown ways. But it also depends on achieving that magical state of working together in productive, transformative interactions. Call it transcendent togetherness, sublime teamwork. Actually, there’s a word for it: call it chemistry.

—Jeff Rosenfeld, Editor-in-Chief

UNDERWATER GLIDER OBSERVATIONS IN THE OXYGEN MINIMUM ZONE OFF CENTRAL CHILE

Giders have become an efficient and reliable oceanographic platform for measuring physical and biogeochemical properties of the seawater, and the global glider fleet is rapidly expanding. In Chile, glider observations have been carried out in very different oceanographic environments, from the mild upwelling region of subtropical northern Chile to the channels of southern Patagonia. Herein, we briefly present observations and results obtained in the oxygen minimum zone off Concepcion (~36°30’S). Many new features have been observed in this region thanks to the relatively high resolution of the glider measurements.

Future plans for the glider program include an oceanic time series off central Chile that will contribute to the regional observing system of the ocean and allow evaluations of low-frequency changes like those associated with El Niño and La Niña events. (Page 1783)

THE STUDIES OF PRECIPITATION, FLOODING, AND RAINFALL EXTREMES ACROSS DISCIPLINES (SPREAD):
AN INTERDISCIPLINARY RESEARCH AND EDUCATION INITIATIVE

Floods and flash floods are, by their nature, a multidisciplinary problem: they result from a convergence of atmospheric conditions, the underlying topography, hydrological processes, and the built environment. Research aimed at addressing various aspects of floods, on the other hand, often follows paths that do not directly address all of these fundamental connections. With
this in mind, the NSF-sponsored Studies of Precipitation, Flooding, and Rainfall Extremes Across Disciplines (SPREAD) workshop was organized and held in Colorado during the summers of 2013 and 2014. SPREAD brought together a group of 27 graduate students from a wide variety of academic disciplines, but with the unifying theme being research interests in extreme precipitation or flooding. During the first meeting of the workshop, groups of graduate student participants designed interdisciplinary research projects that they then began work on over the intervening year, with the second meeting providing a venue to present their results. This article will outline the preliminary findings of these research efforts. Furthermore, the workshop participants had the unique and meaningful experience of visiting several locations in Colorado that had flooded in the past, and then visiting them again in the aftermath of the devastating 2013 floods. In total, the workshop resulted in several fruitful research activities that will advance understanding of precipitation and flooding. Even more importantly, the workshop fostered the development of a network of early-career researchers and practitioners who will be “multilingual” in terms of scientific disciplines, and who are poised to lead within their respective careers and across the scientific community. (Page 1791)

A SIGHT FOR SORE EYES: THE RETURN OF TRUE COLOR TO GEOSTATIONARY SATELLITES

In 1967, at the dawn of the satellite era, the Applications Technology Satellite 3 (ATS-3) provided the first full-disk “true color” images of Earth. With its depiction of blue oceans, golden deserts, and green forestlands beneath white clouds, the imagery captured the iconic Blue Marble in a way that resonates strongly with human perception. After ATS-3, the standard fare of geostationary satellites entailed a single visible band with additional infrared spectral channels. While single-band visible satisfied the basic user requirements of daytime imagery, the loss of true-color capability and its inherent capability to distinguish myriad atmospheric and surface features via coloration left a notable void. Nearly half a century later, with the launch of Japan’s Himawari-8 in October 2014, there is once again a geostationary sensor—the Advanced Himawari Imager (AHI)—containing the multispectral visible bands required notionally for true color. However, it soon became apparent that AHI’s “green” band, centered at 0.51 μm, was not aligned with the chlorophyll reflectance signature near 0.55 μm. As a result, vegetation appears browner and deserts appear redder than legacy true-color imagery. Here, we describe a technique that attempts to mitigate these issues by blending information from a reflective-infrared band at 0.86 μm to form a “hybrid” green band. When combining this method with Rayleigh corrections, AHI’s true-color performance is found to be consistent with that of the optimal 0.55-μm band, offering a stopgap solution adaptable to future satellites of similar design. (Page 1803)

A STATISTICAL FRAMEWORK TO EVALUATE EXTREME WEATHER DEFINITIONS FROM A HEALTH PERSPECTIVE: A DEMONSTRATION BASED ON EXTREME HEAT EVENTS

Issuance of alerts, prior to or during extreme weather events, can be critical to preventing adverse health outcomes. In this paper, data describing episodes of extreme heat are used to demonstrate the application of a statistical framework for evaluating event definitions within the context of human health impacts. Numerous extreme heat event (EHE) definitions appear in the literature but there is a lack of scientific consensus on consistent identification of periods of extreme heat having the potential for such impacts. Ninety-two EHE definitions were operationalized for this region-specific demonstration covering the United States, using station-based meteorological data for the years 1999–2009. Hierarchical cluster analysis was used to group definitions into homogeneous sets, and a representative definition was then selected from each set. The representative definitions were combined with different exposure offsets (e.g., a 1-day lag) and evaluated against daily heat mortality data, using a negative binomial rate regression modeling approach. The EHE definition and exposure offset combinations most closely associated with heat mortality were found to vary with climate region. Those involving high but not extreme meteorological thresholds, and employing a 1-day lag or no lag, showed the strongest associations with heat mortality for all climate regions except the South and Southwest. The framework presented in this study could be applied to other geographic areas, provided the necessary meteorological and health data are available. Additionally, this framework could help regional and national weather offices, in partnership with local and state health departments, identify definitions that are well suited to

ABSTRACTS
issuing alerts and health advisories related to other types of severe weather. (Page 1817)

CoCoRaHS: THE EVOLUTION AND ACCOMPLISHMENTS OF A VOLUNTEER RAIN GAUGE NETWORK
The Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) is a large and growing community of volunteers measuring and reporting precipitation and is making this information broadly available for the research and operational community. CoCoRaHS has evolved through several phases since its beginnings in 1998, first starting as a flood-motivated local Colorado Front Range project, then through a 5-yr nationwide expansion period (2005–09), followed by five years (2010–14) of internal growth and capacity building.

As of mid-2015, CoCoRaHS volunteers have submitted over 31 million daily precipitation reports and tens of thousands of reports of hail, heavy rain, and snow, representing over 1.5 million volunteer hours. During the past 10 years, there has been wide demand for and use of CoCoRaHS data by professional and scientific users with an interest in its applicability to their different areas of focus. These range from hydrological applications and weather forecasting to agriculture, entomology, remote sensing validation, city snow removal contracting, and recreational activities, just to name a few. The high demand for CoCoRaHS data by many entities is an effective motivator for volunteer observers, who want to be assured that their efforts are needed and appreciated.

Going forward, CoCoRaHS hopes to continue to play a leading role in the evolution and growth of citizen science while contributing to research and operational meteorology and hydrology. (Page 1831)

HURRICANE INTENSITY PREDICTABILITY
Weather has long been projected to possess limited predictability due to the inherent chaotic nature of the atmosphere; small changes in initial conditions could lead to an entirely different state of the atmosphere after some period of time. Given such a limited range of predictability of atmospheric flows, a natural question is, how far in advance can we predict a hurricane’s intensity? In this study, it is shown first that the predictability of a hurricane’s intensity at the 4–5-day lead times is generally determined more by the large-scale environment than by a hurricane’s initial conditions. This result suggests that...
future improvement in hurricane longer-range intensity forecasts by numerical models will be most realized as a result of improvement in the large-scale environment rather than in the storm’s initial state. At the mature stage of a hurricane, direct estimation of the leading Lyapunov exponent using an axisymmetric model reveals, nevertheless, the existence of a chaotic attractor in the phase space of the hurricane scales. This finding of a chaotic maximum potential intensity (MPI) attractor provides direct information about the saturation of a hurricane’s intensity errors around 8 m s⁻¹, which prevents the absolute intensity errors at the mature stage from being reduced below this threshold. The implication of such intensity error saturation to the limited range of hurricane intensity forecasts will be also discussed. (Page 1847)

ASIRI: AN OCEAN–ATMOSPHERE INITIATIVE FOR BAY OF BENGAL

Air–Sea Interactions in the Northern Indian Ocean (ASIRI) is an international research effort (2013–17) aimed at understanding and quantifying coupled atmosphere–ocean dynamics of the Bay of Bengal (BoB) with relevance to Indian Ocean monsoons. Working collaboratively, more than 20 research institutions are acquiring field observations coupled with operational and high-resolution models to address scientific issues that have stymied the monsoon predictability. ASIRI combines new and mature observational technologies to resolve submesoscale to regional-scale currents and hydrophysical fields. These data reveal BoB’s sharp frontal features, submesoscale variability, low-salinity lenses and filaments, and shallow mixed layers, with relatively weak turbulent mixing. Observed physical features include energetic high-frequency internal waves in the southern BoB, energetic mesoscale and submesoscale features including an intrathermocline eddy in the central BoB, and a high-resolution view of the exchange along the periphery of Sri Lanka, which includes the 100-km-wide East India Coastal Current (EICC) carrying low-salinity water out of the BoB and an adjacent, broad northward flow (~300 km wide) that carries high-salinity water into BoB during the northeast monsoon. Atmospheric boundary layer (ABL) observations during the decaying phase of the Madden–Julian oscillation (MJO) permit the study of multiscale atmospheric processes associated with non-MJO phenomena and their impacts on the marine boundary layer. Underway analyses that integrate observations and numerical simulations shed light on how air–sea interactions control the ABL and upper-ocean processes. (Page 1859)

ACRIDICON–CHUVA CAMPAIGN: STUDYING TROPICAL DEEP CONVECTIVE CLOUDS AND PRECIPITATION OVER AMAZONIA USING THE NEW GERMAN RESEARCH AIRCRAFT HALO

Between 1 September and 4 October 2014, a combined airborne and ground-based measurement campaign was conducted to study tropical deep convective clouds over the Brazilian Amazon rain forest. The new German research aircraft, High Altitude and Long Range Research Aircraft (HALO), a modified Gulfstream G550, and extensive ground-based instrumentation were deployed in and near Manaus (State of Amazonas). The campaign was part of the German–Brazilian Aerosol, Cloud, Precipitation, and Radiation Interactions and Dynamics of Convective Cloud Systems–Cloud Processes of the Main Precipitation Systems in Brazil: A Contribution to Cloud Resolving Modeling and the GPM (Global Precipitation Measurement) (ACRIDICON–CHUVA) venture to quantify aerosol–cloud–precipitation interactions and their thermodynamic, dynamic, and radiative effects by in situ and remote sensing measurements over Amazonia. The ACRIDICON–CHUVA field observations were carried out in cooperation with the second intensive operating period of Green Ocean Amazon 2014/15 (GoAmazon2014/5). In this paper we focus on the airborne data measured on HALO, which was equipped with about 30 in situ and remote sensing instruments for meteorological, trace gas, aerosol, cloud, precipitation, and spectral solar radiation measurements. Fourteen research flights with a total duration of 96 flight hours were performed. Five scientific topics were pursued: 1) cloud vertical evolution and life cycle (cloud profiling), 2) cloud processing of aerosol particles and trace gases (inflow and outflow), 3) satellite and radar validation (cloud products), 4) vertical transport and mixing (tracer experiment), and 5) cloud formation over forested/deforested areas. Data were collected in near-pristine atmospheric conditions and in environments polluted by biomass burning and urban emissions. The paper presents a general introduction of the ACRIDICON–CHUVA campaign (motivation and addressed research topics) and of HALO with its extensive
BAECC: A FIELD CAMPAIGN TO ELUCIDATE THE IMPACT OF BIOGENIC AEROSOLS ON CLOUDS AND CLIMATE

During Biogenic Aerosols—Effects on Clouds and Climate (BAECC), the U.S. Department of Energy’s Atmospheric Radiation Measurement (ARM) Program deployed the Second ARM Mobile Facility (AMF2) to Hyytiälä, Finland, for an 8-month intensive measurement campaign from February to September 2014. The primary research goal is to understand the role of biogenic aerosols in cloud formation. Hyytiälä is host to the Station for Measuring Ecosystem–Atmosphere Relations II (SMEAR II), one of the world’s most comprehensive surface observation sites in a boreal forest environment. The station has been measuring atmospheric aerosols, biogenic emissions, and an extensive suite of parameters relevant to atmosphere–biosphere interactions continuously since 1996. Combining vertical profiles from AMF2 with surface-based in situ SMEAR II observations allows the processes at the surface to be directly related to processes occurring throughout the entire tropospheric column. Together with the inclusion of extensive surface precipitation measurements and intensive observation periods involving aircraft flights and novel radiosonde launches, the complementary observations provide a unique opportunity for investigating aerosol–cloud interactions and cloud-to-precipitation processes in a boreal environment. The BAECC dataset provides opportunities for evaluating and improving models of aerosol sources and transport, cloud microphysical processes, and boundary layer structures. In addition, numerical models are being used to bridge the gap between surface-based and tropospheric observations.

FOSTERING A COLLABORATIVE ATMOSPHERIC CHEMISTRY RESEARCH COMMUNITY IN THE LATIN AMERICA AND CARIBBEAN REGION

In 2013, the international Commission on Atmospheric Chemistry and Global Pollution (iCACGP) and the International Global Atmospheric Chemistry (IGAC) Project Americas Working Group (iCACGP/IGAC AWG) was formed to build a cohesive network and foster the next generation of atmospheric scientists with the goal of contributing to a scientific community focused on building a collective knowledge for the Americas. The Latin America–Caribbean (LAC) region shares a common history, culture, and socioeconomic issues but, at the same time, it is highly diverse in its physical and human geography. The LAC region is unique because approximately 80% of its population lives in urban areas, resulting in high-density hotspots of urbanization and vast unpopulated rural areas. In recent years, most countries of the region have experienced rapid growth in population and industrialization as their economies emerge. The rapid urbanization, the associated increases in mobile and industrial sources, and the growth of the agricultural activities related to biomass burning have degraded air quality in certain areas of the LAC region. Air pollution has negative implications on human health, ecosystems, and climate. In addition, air pollution and the warming caused by greenhouse gases could impact the melting of Andean glaciers, an important source of freshwater. To better understand the links between air pollution and climate, it is necessary to increase the number of atmospheric scientists and improve our observational, analytical, and modeling capacities. This requires sustained, prioritized, oriented funding as well as stronger collaboration within the LAC region.

CORRECTIONS

In the “Report of the Secretary–Treasurer for 2015” published in May 2016, the 2015 net operating loss of approximately $200,000 was estimated using information available at the time the report was prepared. Based, however, on the auditor’s report published in this issue, the net operating loss for 2015 is closer to $599,000. Similarly, the previously reported investment return in the Society’s unrestricted investments of $8,000 in 2015 should be corrected to read a loss of $46,000.

In the article “Analysis of an Observing System Experiment for the Joint Polar Satellite System” by Stephen Lord et al. published in the August issue of BAMS, footnote 3 is missing from the text on page 1421. The footnote should read,

\footnote{The appellation “worst” is relative and may, in fact, be a very good score when compared to other or past forecast systems.}
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Study Confirms that More Aerosols Lead to Heavier Rainfall

The connection between aerosols and extreme rainstorms has long been theorized, but a new study published in the Proceedings of the National Academy of Sciences is the first to establish a clear link between aerosols and thunderstorm complexes known as mesoscale convective systems, which are the main sources of precipitation in the tropics and midlatitudes. The new study notes that the duration of these storm complexes “can have a large influence on the variability of rainfall, especially extreme rainfall that causes flooding.”

A research team analyzed satellite data of more than 2,400 convective cloud systems. Satellite-based cloud aerosol data typically comes from polar orbiting satellites that travel across the same location on Earth twice a day, but those satellites provide limited information about the lifetime of a convective cloud system. The new study took a unique approach by also utilizing data from geostationary satellites that fly at higher altitudes and remain in the same location relative to Earth’s surface, allowing for observations during storms’ entire lives. The geostationary and polar orbiting satellite data were then combined to provide a new perspective on the cloud systems.

The data showed that an abundance of aerosols in the atmosphere can lengthen the life of a cloud system by 3–24 hours, depending on weather conditions in the vicinity. And the longer the clouds persist and the larger they grow, the more rainfall they can produce.

“A cloud particle is basically water and aerosols,” explains the study’s lead author, Sudip Chakraborty, who recently received his Ph.D. from the University of Texas. “It’s like a cell. The aerosol is the nucleus and the water is the cytoplasm. The more aerosols you have, the more cells you get. And if you have more water, you should get more rain.”

The research indicated that about 20% of the variability in the lifespan of a cloud system over South Asia and Latin America could be attributed to the amount of aerosols in the atmosphere, with a lesser influence over Africa—about 8% of the variability there is influenced by aerosols.

Mesoscale convective systems can persist for more than 12 hours and stretch over several hundred kilometers. The new paper establishes the considerable impact that aerosols have on the lifespan of these systems, although coauthor Rong Fu of the University of Texas notes that meteorological conditions—such as wind shear, relative humidity, and available convective energy—still have the greatest influence.

This is like a bulldozer at 30 meters a second, going into this water, and pushing it forward.”

—MARTIN P. LÜTHI of the University of Zurich (UZ), on the force created when 900,000 cubic meters of ice broke from the Greenland glacier called Eqip Sermia and plunged 200 meters into a fjord. Lüthi and fellow UZ scientist Andreas Vieli studied the 2014 event and the tsunamis it caused—an immediate wave of about 50 meters in height, and another 10–15-meter-high tsunami that occurred less than 3 minutes later more than 4.5 kilometers away. They found that the Eqip Sermia glacier has accelerated its losses and its retreat from the coast to the center of the Greenland ice sheet in recent years, which has created a higher cliff face that extends as much as 200 meters out of the water within the fjord, leading to tsunamis unprecedented in size. “I’ve never seen any glacier with such a high front,” Lüthi states. “This is just not stable, that’s why it collapses constantly.” While Lüthi surmises that the unusual shape of the glacier is temporary (the cliff face was only 50 meters high before 2012), he notes that the study, published recently in The Cryosphere, highlights the fact that “glaciers are changing like crazy, really rapidly. Everything changes, and people cannot rely on their experience from generations. Suddenly things happen that nobody thought of before.” [SOURCE: The Washington Post]
As warming of the Arctic region has accelerated in recent decades and led to an increase in ice melt, a number of recent unusually chilly winters have occurred in the Northern Hemisphere, giving rise to the phrase “Warm Arctic, Cold Continents” by some who have theorized the two are connected. However, new research published in *Geophysical Research Letters* suggests that “[i]t’s just by chance and not because of Arctic sea ice loss or human-caused factors that ‘Cold Continents’ has happened more often in recent years,” says coauthor Judith Perlwitz of the Cooperative Institute for Research in Environmental Sciences (CIRES).

Perlwitz and colleagues studied multiple climate models to determine the effects of Arctic sea ice loss on both the Arctic atmosphere and temperature patterns in the lower latitudes. They found that sea ice loss is in fact warming the Arctic, but determined that “recent Northern Hemisphere cold winters were the result of naturally occurring climate variations, and not due to remote effects of Arctic sea ice loss,” states lead author Lantao Sun of CIRES.

For example, the researchers found that “winter cooling trends over Eurasia are accompanied by a strengthening of the Siberian High, which brings more cold air from the Arctic into central and eastern Asia,” Perlwitz explains. They discovered that a similar natural pattern influences cold winters in North America.

“These well-known circulation patterns are the major drivers of the wintertime temperature variability in northern midlatitudes, and recent Arctic sea ice loss does not substantially affect them,” Perlwitz says.

The study found that the loss of Arctic sea ice instead has a warming effect on typically cold air masses that can periodically move into the midlatitudes, leading to fewer cold spells and less variability in daily temperatures. They suggest that “Warm Arctic, Warm Continents” is a more apt phrase to describe human influence on temperatures in the Northern Hemisphere, as most of their model runs depicted warming in both regions. As a result, they expect...
the uncommonly cold Northern Hemisphere winters that inspired the original phrase to become less common. [Source: CIRES]

**What Is Causing the California Drought, and How Long Will It Last?**

Despite a strong El Niño in the winter of 2015–16, a severe drought that started in 2011 continues to linger throughout much of California. Two recent studies published in *Geophysical Research Letters* focus on this enduring event, with one making a surprising discovery about what is causing the multiyear drought and the second investigating how persistent it might be.

In the study of the drought’s causes, researchers looked at 30-year datasets of atmospheric pressure, ocean evaporation, precipitation, and surface wind speed—all elements that impact California’s water cycle—for areas at and near the U.S. West Coast. They also utilized a mathematical method for tracking moisture and high-resolution model simulations, and their research indicated that while most California precipitation is caused by evaporation over the Pacific Ocean saturating the air as it moves inland and is lifted by terrain, the amount of water that evaporates is not a significant influence on variability in the state’s precipitation except for certain instances of extremely heavy flooding. According to the study’s lead author, Jiangfeng Wei of the University of Texas (UT), this is because of the “relatively weak variability” in the amount of water that evaporates from that ocean region on a year-to-year basis, which consequently leads to minimal evaporation fluctuations and their influence over rainfall amounts.

Rather, Wei and colleagues discovered that “large-scale atmospheric circulation, or wind, actually controls the ocean evaporation and also controls the transfer of evaporated moisture from the ocean to California.” They found that disruptions in atmospheric circulation influence factors that lead to greater or less amounts of rainfall, and therefore have the greatest impact on drought. Specifically, the researchers noted a “very rare event”: a high-pressure system, sometimes called the “Ridiculously Resilient Ridge”—which developed because of a Pacific sea surface temperature pattern—that is agitating the atmospheric circulation and causing the current drought. These findings provide new insight into the water cycle and its connection to extreme events, and “will ultimately help us make better predictions” about droughts and floods, according to coauthor Zong-Liang Yang.

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**ECHOES**

“It felt like a sore thumb.”

—**CHRIS HUGHES,** University of Liverpool scientist, on a low-pitched whistle that was recently discovered emanating from the Caribbean Sea. Researchers were looking at models across the Caribbean in order to better understand ocean dynamics when they came across the noise. Noticing that the models indicated pressure oscillations across the basin that didn’t make sense and stuck out like the proverbial thumb, they investigated further, finding what they’ve now dubbed the “Rossby whistle.” The sound, it turns out, is caused by a Rossby wave traveling west across the ocean. When the current becomes unstable, it excites resonance. While the sound is too low to be heard by humans, the Rossby whistle is strong enough to have been picked up from space. The researchers plan further research to better understand how it affects ocean dynamics; their initial results on the whistle were published in a recent issue of *Geophysical Research Letters.* [Source: sciencealert.com]
also of UT. The researchers next plan to study how these dynamics affect rainfall in Texas.

In the second study, researchers analyzed 65 years of snowpack data (1951–2015) taken from satellites and California records and calculated that the water that the state didn’t receive from the snowpack over the four years of the drought was the greatest cumulative shortfall in the entire studied period, at –22 km³. They then utilized the historical record to develop probability models that predict the snowpack volume year-by-year, and found that 14 of the 65 studied years would officially be considered as a drought. While the deficient snowpack recovered within a year in all but one of those instances, the study revealed that the current drought had only a 7% chance of being “fully alleviated” in 2016. Instead, the model predicted a complete rebound from the drought would take about 4.4 years.

“The main take-home is thinking about drought over longer time scales,” notes the study’s lead author, Steve Margulis of UCLA. “The first wet year doesn’t necessarily solve the longer-term problem.” [Sources: University of Texas at Austin, newsdeeply.com, Los Angeles Times]

**“Electric Wind” Drained Venus of Its Water**

Past studies have suggested that millions of years ago, oceans similar to Earth’s were once present on Venus, but then that planet’s extreme temperatures (around 860°F) caused them to completely boil away. But scientists have been puzzled as to why the atmosphere of Venus, which has about 100 times the pressure of Earth, has 10,000–100,000 times less water than the atmosphere of Earth. A new paper in Geophysical Research Letters reveals that the second planet from the Sun has an electric field so strong that it is “capable of sucking the water from Venus by itself,” according to lead author Glyn Collinson of NASA’s Goddard Space Flight Center. The researchers call this intense electric force, which allows ions to overcome gravity and escape to space, an “electric wind.” The finding could aid scientists in identifying the location and size of habitable areas (i.e., areas with life-sustaining water) around other stars.

Collinson and colleagues utilized an electron spectrometer on the Venus Express satellite to monitor electrons surging out of the upper atmosphere of Venus. They were surprised to discover that the electrons were not moving at their expected speed, and they found that the pull of the planet’s electric wind, or field, was the reason. They measured the change in electron speed across the...
field to determine its strength and found it was significantly stronger than they expected—about 10 volts, which is at least five times stronger than Earth’s electric field potential. According to the study, the higher strength of this electric potential is what helped force water off Venus and out of its atmosphere. Water molecules ascending into the upper atmosphere were broken up by sunlight into hydrogen and oxygen ions. The faster hydrogen ions easily overcame the planet’s gravity, but because the electric field is so strong, the heavier electrically charged oxygen ions were also able to escape.

“If you were unfortunate enough to be an oxygen ion in the upper atmosphere of Venus then you have won a terrible, terrible lottery,” Collinson says. “You and all your ion friends will be dragged off kicking and screaming into space by an invisible hand, and nothing can save you.”

The researchers were uncertain what makes the electric wind of Venus so powerful, but theorize that it is connected to the relatively close proximity of the planet to the Sun, which makes the ultraviolet sunlight there twice as bright as that reaching Earth.

“It’s amazing, shocking,” Collinson says. “We never dreamt an electric wind could be so powerful that it can suck oxygen right out of an atmosphere into space. This is something that has to be on the checklist when we go looking for habitable planets around other stars.” [Source: American Geophysical Union]

**STUDY FINDS OCEAN CIRCULATION SPURRED ICE AGE TEMPERATURE CHANGES**

Near the end of the last ice age, temperatures in the Northern Hemisphere oscillated markedly in periods that lasted about 1,500 years. The cause of this variability has long puzzled scientists, although the Lamont-Doherty Earth Observatory’s L. Gene Henry notes that “[p]eople have long supposed this link between overturning [ocean] circulation and these abrupt climate events.” Henry was the lead author of a recent paper in *Science* that he says “implicates the ocean” in the temperature changes, highlighting the sensitivity of ocean circulation at a time when an abundance of freshwater is being introduced into the Atlantic because of melting sea ice and glaciers.

Henry and colleagues focused their study on the glacial interval called “marine isotope stage 3,” which occurred between 60,000 and 25,000 years ago. For that period, they looked at the Atlantic Meridional Overturning Circulation (AMOC), a conveyor belt of currents that push warmer surface water from the tropics north toward the northern high latitudes—for example, within the Gulf Stream—and colder deep water south from the North Atlantic Ocean. The scientists studied three kinds of chemical tracers—two isotopes of uranium decay as well as carbon-13—in a sediment core taken from deep in the North Atlantic.

The tracers indicated that during the studied period, every occasion when sea surface temperatures became colder was preceded by the AMOC slowing down (and in those instances it was transporting less heat from the tropics). In some cases, called Heinrich events, the AMOC almost stopped completely when huge chunks of icebergs broke off the Laurentide ice sheet and discharged large amounts of freshwater into the ocean.

Those changes were also evident in the atmosphere. With each occurrence of cooling sea surface temperatures, every corresponding instance of changing air temperatures followed a similar sequence: a cooling that occurred in a span

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[Source: American Geophysical Union]
In the United States, the number of wildfires larger than 1,000 acres has doubled since 1970, and last year for the first time more than 10 million acres burned throughout the country. All of this activity is creating a greater risk to life and property, which means keeping track of the fires has become increasingly important. A new wildfire-monitoring website created and maintained by wxshift.com—a climate information project of Climate Central—provides a current summary of every wildfire throughout the country. Located at http://wxshift.com/climate-change/climate-indicators/us-wildfires, the page spotlights all active fires on a U.S. map and provides information on acres burned for each one, as well as statistics for all the states currently experiencing fires, including the total number of people at risk and yearly wildfire trends for the state. The site also has explanatory video and text on the significance of wildfires, and links to related wxshift.com news stories.

While the researchers noted that further study is necessary to determine whether the AMOC changes generated the temperature decrease or were an effect of an earlier trigger, the new study “supports the view that changes in ocean circulation were at least in part responsible for causing abrupt climate changes,” Henry states. He also noted that the original cause of the circulation shifts “remains a mystery.” [Source: Lamont-Doherty Earth Observatory]
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Worldwide, the use of autonomous underwater gliders has spread rapidly, and they have become an important tool in ocean observing systems. Most gliders are equipped with sensors that can measure the physical and biogeochemical properties of the seawater in the first kilometer of the ocean. Small changes in buoyancy allow underwater gliders to move horizontally and vertically by controlling the dive and climb angles and the horizontal direction (Sherman et al. 2001; Davis et al. 2003; Rudnick et al. 2004). Gliders can cover relatively large distances with very low power consumption. The standard scientific equipment carried onboard many ocean gliders includes conductivity, temperature, and depth (CTD) and optical biogeochemical sensors for reading dissolved oxygen, fluorescence, and turbidity levels. Recently, new instruments and sensors such as probes for turbulent microstructure measurements (e.g., Wolk et al. 2009; Palmer et al. 2015) and small current profilers that use acoustic Doppler (e.g., Todd et al. 2011; Siegel and Rusello 2013) have been developed to be used in gliders. Similarly, other new sensors are rapidly being adapted or developed to be mounted on underwater gliders. Presently, many gliders are equipped with oxygen sensors, and they are being used to explore and monitor different oxygen minimum zones (OMZs) around the world.

OMZs are oceanic regions in which waters at upper intermediate depths (~100 to ~800 m) present dissolved oxygen (DO) concentrations persistently lower than ~0.5 mL L⁻¹ (20 µmol kg⁻¹; Kamykowski and Zentara 1990). OMZs result from a combination of ventilation, organic matter respiration, and water-mass age. Their main ventilation occurs remotely in places where the characteristic water mass is formed (i.e., where it is last in direct contact with the atmosphere). Oxygen consumption, on the other hand, results mainly from the microbial aerobic oxidation of organic matter that takes place continuously within a water mass as it travels through the global ocean at depth. Consequently, for a given respiration rate, older water masses should have lower DO values (Karstensen et al. 2008).

Major modern oceanic OMZs are located in the Arabian Sea and in the eastern boundary of the Pacific Ocean (Kamykowski and Zentara 1990). They have become relevant in the context of global change, since models predict a significant reduction of DO in the ocean’s interior and, consequently, their intensification and expansion (Metear and Hirst 2003; Schmittner et al. 2008). Such changes should impact marine ecosystems (Grantham et al. 2004) as well as global biogeochemical cycles (Codispoti 2010). Analyses of historical data appear to support the predictions of reductions in the DO content in the tropical open ocean (Stramma et al. 2008) and in coastal ecosystems (Grantham et al. 2004). However, current ocean
models, which include the main anaerobic processes, are limited in their ability to reproduce DO variability—that is, the distribution and intensity of the OMZ (Najjar et al. 2007; Keeling et al. 2010). Moreover, anaerobic processes alone cannot account for the nitrogen cycling that takes place within the oxygen-depleted waters (Lipschultz et al. 1990; Lam et al. 2009).

One of the limitations to understanding the dynamics of OMZ has been the inability to carry out observations with enough temporal and spatial resolution to evaluate the persistence of oxygen-depleted waters, seasonal and higher frequency changes, and the importance of energetic oceanographic processes like mesoscale eddies that contribute to mixing and the ventilation of the OMZ.

Underwater gliders offer a unique opportunity to sample the OMZ with relatively high resolution without using costly oceanographic platforms. Observations made with gliders have been carried out in different regions off Chile since 2009, including the OMZ. Herein, we show observations carried out by the underwater glider group at the University of Concepcion in the southern tip of the OMZ off central Chile and describe new observational initiatives using underwater gliders in the eastern South Pacific for the coming years.

**Measurements of the Oxygen Minimum Zone off Central Chile.**

In the eastern subtropical South Pacific, the OMZ is a permanent feature that extends along the western coast off South America between ~50-m and 800-m depth. Its intensity and vertical and horizontal extension vary along the coast (Fuenzalida et al. 2009; Llanillo et al. 2012), but this layer can be tracked as far south as ~48°S (Silva and Neshyba 1979), with a core centered between 200- and 300-m depth. Off central Chile, the OMZ is located on top of the relatively well-ventilated Antarctic Intermediate Water. The OMZ is more intense near the coast than farther offshore and, on average, it extends several tens of km offshore off central Chile (Fuenzalida et al. 2009). During the upwelling season, its upper boundary is shallow (25–50-m depth), and oxygen-depleted waters may cover a large fraction of the continental shelf (e.g., Paulmier et al. 2006; Sobarzo et al. 2007; Paulmier and Ruiz-Pino 2009). The high productivity observed near the coast may generate local minima of DO when the degradation of organic matter induces intense oxygen consumption (Paulmier et al. 2006).

A nominal transect of about 150–180 km in length has been repeated on several occasions off Concepción (36°30'S) since 2009 (Fig. 1) using Teledyne Webb research Electric Slocum gliders (rated for 1,000-m depth). The horizontal speed of the deep Slocum glider, relative to the water, is nominally ~40 cm s⁻¹ (using a dive angle of 26°; the maximum change in volume of these gliders is 500 cc and their total volume is 56 L). Our own estimates, based on different glider missions, show similar velocities when the glider is far enough from the surface or from the maximum diving depth, despite the fact that speed depends on the net buoyancy of the glider, set by the ballasting. As the underwater glider can reach ~1,000-m depth, we have been able to sample the entire vertical structure of the OMZ off central Chile.

Glders were equipped with optical oxygen sensors (Aanderaa Data Instrument oxygen optode model 3830), which are regularly checked in our laboratory using a two-point calibration curve by using one solution of 0% oxygen and one that was 100% saturated with air. Details of the sensor and the physical principles involved in the measurements are described in Körtzinger et al. (2005) and Uchida...
et al. (2008). For the calculation of DO, a fourth-order polynomial in P is used, where the polynomial coefficient C depends on temperature. The time constant of the temperature sensor from the optode is large (~15 s), even for the slow vertical velocity of the glider (~0.2 m s$^{-1}$). In regions with large vertical temperature gradients (e.g., the thermocline), it may be better to use the much faster, more precise temperature sensor from the CTD to calculate DO in the glider. Unfortunately, we did not record the phase P data from the optode sensor for the measurements taken prior to January 2014. Thus, oxygen data were calculated from the optode temperature sensor. Salinity and pressure corrections were estimated based on the polynomial given by Aanderaa.

The new glider data enable us to estimate the offshore extent of the OMZ off Concepcion and to visualize its large spatial variability (Fig. 2). Some of this variability seems to be related to mesoscale eddy activity that transports coastal waters from the OMZ offshore (e.g., Hormazabal et al. 2013). Note the close relationship between the minimum oxygen and maximum salinity values (Fig. 2). As salinity acts like a passive tracer, much of the water observed offshore in the core of the OMZ is related to high-salinity Equatorial Subsurface Water (ESSW), which dominates the subsurface waters over the continental shelf and upper slope.

The new dataset also allows us to describe the seasonal change in DO off Concepción (Fig. 3). Large changes in DO occur over the continental shelf and offshore. The total volume, per unit of width, of water with very low DO (< 1 mL L$^{-1}$) observed in March 2011 was about twice that of the volume observed in June and September 2010. These changes are related to changes in the poleward Peru-Chile Undercurrent, which modulates the transport of ESSW (a water mass characterized by very low DO) along with the intense mesoscale variability observed in this zone.

During the austral summer of 2010–11, La Niña conditions prevailed in the tropical Pacific. Off central Chile, interannual winds showed positive (upwelling favorable) anomalies during all of 2010. Interannual coastal sea level anomalies were consistently negative. Nevertheless, during 2011, interannual alongshore wind anomalies decreased and small negative
(downwelling favorable) anomalies prevailed during the second half of 2011. On the other hand, sea level anomalies in Concepción were rather small, but still negative, during 2011. Interannual sea level anomalies off central Chile are inversely related to changes in the poleward subsurface flow (negative sea level anomalies are followed by a weakening of the subsurface poleward flow; Pizarro et al. 2001). As this flow transports low oxygen water southward off Chile, it also can modulate the intensity and offshore extension of the OMZ off Concepcion.

Although the sea level suggested that the poleward flow was anomalously weak, direct current observations from the shelf break at 36°33’S (Fig. 4) showed that the glider transect of March 2011, which showed very low values of oxygen with a much longer extension offshore (Fig. 3), took place just after an intense event of subsurface poleward flow (see stick diagrams of the current below 80-m depth in Fig. 4). This event lasted from the last week of January to the middle of March. The poleward current shows intraseasonal variability probably related to coastal trapped waves. These intraseasonal waves largely modulate the variability of the Peru-Chile Undercurrent over the continental shelf and slope off Peru (Huyer et al. 1991) and Chile (Shaffer et al. 1997; Pizarro et al. 2002), and may also contribute to the modulation of the OMZ variability off central Chile. Additional current and oxygen measurements based on moored sensors (not shown here) over the continental shelf off Concepción support this idea.

Near the coast, the distributions of oxygen, salinity, and temperature show the effects of seasonal variability in upwelling (Fig. 2). In summer, the oxycline rises over the continental shelf and hypoxic water, unsuitable for fish and other species, occupies most of the water column. Figure 2 (left panels) shows a front near the surface over the shelf break. This front seems to be related to the cold water upwelled off Punta Lavapie, which is then transported northward by a coastal jet that flows along the shelf break (Fig. 1a; see also Letelier et al. 2009 and Aguirre et al. 2012). Note that the upwelled
waters near the coast have relatively higher salinities than the offshore waters, consistent with the idea that ESSW is one of the main water sources for upwelling off Concepción.

In the frontal region and over the outer shelf, surface waters are slightly saltier than the waters located immediately shoreward, over the midshelf, consistent with the presence of a coastal jet that transports upwelling waters northward from Punta Lavapie, as suggested by the cooler tongue visible in the satellite SST image (Fig. 1, left). These are some of the specific features observed in the ocean off Concepcion. A detailed analysis and discussion of these features is beyond the scope of the present note. However, further studies detailing the different topics delineated above are presently in development.

OBSERVING THE OCEAN OFF CENTRAL CHILE WITH GLIDERS: FUTURE PLANS.

Since late 2002, a monthly, ship-based, oceanographic time series has been maintained on the continental shelf off Concepción (36.5°S), a well-known zone of intense coastal upwelling. This time series includes a core suite of physical, biological, and biogeochemical parameters and has been the basis for a number of oceanographic studies (e.g., Escribano and Morales 2012). This program has also provided the opportunity for graduate and undergraduate students to conduct thesis research and in situ experiments.

Nevertheless, vast oceanic regions of the eastern South Pacific off Chile remain very poorly sampled. As part of the activities of the recently created Millennium Institute of Oceanography (IMO), a new center for oceanographic research about the southeastern Pacific Ocean, we plan to carry out repeated glider sections twice a year (Fig. 5), extending from Robinson Crusoe Island (~33°40’S, 78°40’W in the Juan Fernandez archipelago) to Concepción Bay at the continent coast (~36°30’S). The transect extends for approximately 600 km and will take about 1 month to complete.

These glider-based time series will make it possible to address a variety of new research problems. Interannual changes occur in the transport of the different flows conforming the Peru-Chile Current System, as do changes in water mass composition, including Antarctic Intermediate Water and the southern tip of the OMZ. Important interannual changes are expected to occur associated with the El Niño-La Niña cycles. Mesoscale eddies transport coastal waters westward (Hormazabal et al. 2013) with very low DO and relatively high salinity (Fig. 2, right panels). This eddy-induced transport may play an important role in shaping the OMZ off Chile. The time series of glider transects will capture mesoscale eddies at different distances from the coast and will cover a significant fraction (up to 1,000-m depth) of the typical eddy vertical scale. This information, together with satellite altimetry, will allow us to assess the evolution of the mesoscale eddies as they travel offshore and to evaluate their role in the zonal transport off central Chile.

The glider transects are initially planned to be occupied twice a year. They are mainly intended to analyze the spatial structure of mesoscale eddies and seasonal and interannual changes in transport, temperature, salinity, and dissolved oxygen in the upper kilometer of the ocean. Seasonal and interannual ocean variability off south central Chile remains poorly explored. Our concept of the oceanic circulation and water mass variability in this region rests in a few sparse oceanographic observations, and its estimates are very uncertain. We think this glider observing program will contribute to reducing these uncertainties. The glider observations will also complement the monthly time series oriented to study the coastal upwelling cell over the continental shelf near 36°30’S (i.e., at the coastal extreme of the glider transect). Furthermore, an oceanic mooring near Robinson Crusoe Island, at the other extreme of the glider transect, has been recently (October 2015) deployed by IMO. Another deep ocean mooring, at 75°W close to the glider path, will be deployed during 2017. These moorings (equipped with current, temperature, conductivity, and oxygen sensors) are planned to be maintained for several years, making it possible to analyze temporal variability associated
with mesoscale eddies and the seasonal cycle of the flows (along with other high-frequency processes). These time series will greatly complement the high spatial resolution observations from the ocean gliders.

The new oceanographic data collected by the gliders will be available to the entire scientific community, helping to validate regional model simulations. We also expect to motivate young researchers and graduate students to analyze regional oceanographic problems, and we would also like to contribute to the global oceanic observing systems.

ACKNOWLEDGMENTS. We greatly appreciate all of the graduate and undergraduate students who collaborated with the glider team of the University of Concepción: Dernis Mediavilla, Amaru Fernandez, Roxana Rodriguez, and Cristian Ruiz, and the electronic engineer, Victor Vil lagran, from the Department of Geophysics. The authors are thankful to Osvaldo Ulloa for insightful comments and ideas at various stages of this research. Jack Barth, Anatoli Erofeev and the ocean glider team from Oregon State University have permanently supported our glider group. We greatly appreciate comments from Billy Kessler and an anonymous reviewer. This research was supported by FONDECYT project 1120019 and the Millennium Scientific Initiative Grant IC120019. The acquisition and operation of the gliders were supported by COPAS, Sur-Austral (PFB-31 CONICYT), and the Microbial Initiative in Low Oxygen Areas off Concepción and Oregon, financed by the Gordon and Betty Moore Foundation.

FOR FURTHER READING


Llanillo, P. J., J. L. Pelegri, C. M. Duarte, M. Eme lianov, M. Gasser, J. Gourrion, and A. Rodriguez-Santana, 2012: Cambios latitudinales y zonales en...


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Floods and flash floods can be deadly, destructive to property and infrastructure, and have wide-ranging impacts on people and ecosystems. There also remain important and unresolved questions about how floods have changed over time and how they may change in the future. To fully understand floods and their impacts, it is important to consider what happens in the atmosphere to produce heavy precipitation (a question for the field of meteorology), what happens to the water once it reaches the ground (hydrology), how the flooding affects people (economics, sociology, psychology, emergency management, and many other fields), how the flooding impacts ecosystems (ecology, watershed science), and how floods are likely to change in the future (climate science, policy). These diverse effects demonstrate that floods are by nature an interdisciplinary problem for researchers and practitioners.

Considering the multidisciplinary nature of floods, but the often disconnected lines of research conducted to address various aspects of floods, efforts to integrate the expertise offered by different disciplines would seem to have the potential to bear great fruit for both scientific understanding and societal benefit. With this in mind, the Studies of Precipitation, Flooding, and Rainfall Extremes across Disciplines (SPREAD) workshop was organized and held during the summers of 2013 and 2014. SPREAD brought together a group of 27 graduate students from a wide variety of academic disciplines, including meteorology, hydrology, psychology, economics, engineering, history, geography, science and technology studies, and more (Table 1), but with the unifying theme being research interests in extreme precipitation or flooding. Applications for the workshop were solicited by contacting university faculty members to encourage their students to apply and by posting the announcement widely on relevant listservs and social media. Forty-five applications were received and 27 participants were selected based on their interests and experience in interdisciplinary research and the goal of having a broad range of academic disciplines represented.

The SPREAD workshop was inspired by, and in many ways modeled after, other recent efforts to initiate and promote research activities that consider the intersection of weather, climate, and society, including the Weather and Society*Integrated Studies (WAS*IS) workshops; the Dissertations Initiative for the Advancement of Climate Change Research (DISCCRS); the Summer Colloquia sponsored by the Advanced Study Program at the National Center for Atmospheric Research (NCAR); and the Water and Society workshops. These initiatives have led to cohorts of researchers and practitioners with not only expertise in a particular specialty, but literacy and interest in integrating methods and knowledge from

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**AFFILIATIONS:** SCHUMACHER—Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

**CORRESPONDING AUTHOR:** Prof. Russ Schumacher, Department of Atmospheric Science, Colorado State University, 1371 Campus Delivery, Fort Collins, CO 80523

E-mail: russ.schumacher@colostate.edu

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1 In addition to the primary graduate student participants, four undergraduate students also attended and participated in portions of the workshop.
those with other specialties. In other words, they are “multilingual,” in the sense that they can understand and speak the language of numerous disciplines. This idea was one of the motivations and underpinnings for SPREAD, which was sponsored by the National Science Foundation under a CAREER grant to integrate research and education in innovative ways. In particular, graduate students were recruited to be the participants in the workshop for several reasons. Graduate students are typically at the beginning of their research careers, yet are generally working at the cutting edge of their disciplines (or multiple disciplines). They are at the stage of their careers when learning multiple “scientific languages” can be a great advantage for both their thesis/dissertation research projects and their future career prospects. They are also being trained as the future leaders in their field(s), and, with a broad perspective on important unsolved problems of societal importance, have the potential to initiate new and transformative research directions.

The goals of the workshop included 1) identifying current research questions and proposing concrete ideas to address these questions by incorporating methods and data from multiple disciplines; and 2) developing a network of early-career researchers who are ultimately able to do innovative work not only in their disciplinary “home,” but with a broader perspective, as well. The workshop was conducted over two summers so that research ideas could be developed during the first meeting, and then individuals or subgroups could make progress toward those research objectives during the intervening year and present the results at the second meeting. The workshop was held on 16–21 June 2013 at Colorado State University in Fort Collins, and on 23–25 July 2014 at NCAR in Boulder.

### Table 1. Graduate student participants in SPREAD, highlighting the diversity of disciplines of study.

<table>
<thead>
<tr>
<th>Student</th>
<th>University</th>
<th>Graduate program discipline</th>
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<tr>
<td>Alex Bryan</td>
<td>Michigan</td>
<td>atmospheric science</td>
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<tr>
<td>Linyin Cheng</td>
<td>UC Irvine</td>
<td>civil engineering</td>
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<tr>
<td>Jessica Erlingis</td>
<td>Oklahoma</td>
<td>meteorology/hydrology</td>
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<tr>
<td>Melissa Haeffner</td>
<td>Colorado State</td>
<td>human/environment interaction</td>
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<tr>
<td>Chris Hanlon</td>
<td>Penn State</td>
<td>meteorology</td>
</tr>
<tr>
<td>Jill Hardy</td>
<td>Oklahoma</td>
<td>meteorology/hydrology</td>
</tr>
<tr>
<td>Jennifer Henderson</td>
<td>Virginia Tech</td>
<td>science/technology studies</td>
</tr>
<tr>
<td>Stephanie Hoekstra</td>
<td>East Carolina</td>
<td>geography/meteorology</td>
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<td>Zoé Kavanagh</td>
<td>York</td>
<td>disaster and emergency management</td>
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<td>Jared LeClerc</td>
<td>Washington</td>
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<td>Ben Miller</td>
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<td>economics</td>
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<td>Annareli Morales</td>
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<td>John Peters</td>
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THE WORKSHOP. The agenda for the 2013 workshop was organized so that the first two days consisted of presentations from prominent researchers and practitioners in interdisciplinary science and research. The opening keynote presentation was given by Bill Hooke of the AMS Policy Program, who outlined the importance of working at the interface of science and society, and how flood policy has evolved over time. Other presenters included Eve Gruntfest (National Science Foundation), Rebecca Morss (NCAR), J. J. Gourley (National Severe Storms Laboratory), Dave Gochis (NCAR), Kelly Mahoney (NOAA), and a remote presentation by Marshall Shepherd in conjunction with a similarly themed summer course at the University of Georgia. In addition to the results of their own work, these presenters also discussed their own successes and challenges in conducting interdisciplinary research. The students also gave brief presentations about their areas of research, and took part in a hands-on exercise with Geographic Information Systems (GIS) software. In this exercise, the participants divided into subgroups and were provided with several datasets from the deadly 31 May 2013 tornadoes and flash flood in central Oklahoma, including radar, precipitation, and streamflow observations, National Weather Service (NWS) warnings, storm reports, and articles from news media. The participants were able to integrate these various sources of information to better understand the spatial and temporal scales that must be considered in a multihazard event such as this.

On day 3, attention turned to historical floods that had occurred in Colorado, including the Fort Collins flash flood of 1997, the Big Thompson flood of 1976, and the 1982 Lawn Lake dam break flood in Rocky Mountain National Park. Marsha Hilmes-Robinson, floodplain manager for the City of Fort Collins, offered insights about the lessons learned and actions taken after the deadly Fort Collins flash flood, and then the group departed to visit several sites in person, led by hydrometeorologist Matt Kelsch of UCAR/COMET. This trip in June 2013 proved particularly meaningful when in September 2013 many of the same areas experienced historic flooding. During the 2013 workshop, Matt Kelsch again led a tour to areas that were flooded in September 2013, which included some of the same locations that the group visited in June 2013. Several participants noted that seeing the long-term effects of the different types of floods in person, along with the “before-and-after” perspective between 2013 and 2014, were valuable for providing physical and societal context for their research (Fig. 1).

Fig. 1. Photos of Viestenz-Smith Mountain Park, in Big Thompson Canyon between Loveland and Estes Park, Colorado. (a) SPREAD participants in June 2013, inspecting the ruins of a hydroelectric plant destroyed in the 1976 Big Thompson flood, with the building housing the current hydroelectric plant in the background. (Photo courtesy of Jen Henderson.) (b) Aerial photo in September 2013. The building seen in the top photo is in the upper right of this photo, with trees strewn atop it. (Photo courtesy of the Civil Air Patrol.) (c) SPREAD participants in July 2014, with the park under repair. (Photo by the author.)
Motivated by the field trip and other discussions during the week, one recurring topic of conversation and debate was the idea of return periods for rainfall and flooding (e.g., the “100-year flood”). Return periods are formally defined by an annual exceedance probability: the probability, based on historical observations, that a given amount of rain will fall at a location, or a river or creek will reach a certain level, in any given year. These probabilities are then often converted into return periods, so that an event with a 1% chance of occurring in any year is referred to as a “100-year event.” Along Spring Creek in Fort Collins, a monument indicates the water level for the 25-, 50-, and 100-year floods, along with the high-water mark from 1997 (which is considerably higher than the other levels). However, important questions were raised about how a monument like this would be interpreted by those visiting the site, such as whether this would make residents more likely to prepare for future floods, or instead lead to complacency. Some of the student participants are actively working on statistical methods to improve the estimation of return periods, while Brian Rumsey (history, University of Kansas) has conducted research on how the “100-year flood” became so widely used for policy and decision-making. Because flood and rainfall return periods are used for the design of infrastructure as well as for public understanding of floods, sorting out the complex set of questions surrounding how they are developed and communicated is a timely and naturally interdisciplinary research problem.

These discussions then led into the other primary objective of the workshop: developing multidisciplinary research projects that could be carried forward over the year in between the formal meetings of the workshop, and potentially beyond. These vibrant discussions over the last two days of the 2013 workshop led to the initiation of several studies that will be briefly described in the next section.

**RESEARCH PROJECTS INITIATED AT SPREAD.** The development of a Flash Flood Severity Index (FFSI). A large group of workshop participants, led by Amanda Schroeder (atmospheric science, University of Georgia, and now an NWS forecaster), has worked together to design a study with the objective of quantifying the severity and impact of flash floods. Other notable natural hazards have well-established scales that are used to classify their severity, but no such scale exists for flash floods. One possible reason for this is that it is very difficult to objectively categorize flash floods, precisely because they are a combination of meteorological, hydrological, and societal factors. For example, the same amount of rainfall over different watersheds can lead to very different flood responses, and an equally swift rise in a creek or river will have varying impacts depending on the infrastructure and population density of the surrounding area.

To work toward the development of a flash flood severity index (FFSI), this group has employed a variety of research methods representing multiple disciplines. Semistructured interviews were conducted with NWS forecasters, hydrologists, and managers to better understand their current practices in issuing flash flood warnings and to assess their needs for classifications of the impact of flash floods. Nearly 70 flash floods representing a spectrum of impacts and geographic locations were analyzed using meteorological and hydrological data and flood reports from official sources and media reports. Based on the results of the interviews and case studies, a preliminary index was proposed with five categories ranging from minor to catastrophic flooding. With further development and refinement based on feedback from the scientific and operational community, this index could be used in postevent assessment (akin to the Enhanced Fujita scale for tornadoes) and provide useful historical context to NWS staff and researchers as they evaluate the impacts of flash floods in the future. The detailed results of this research and the proposal for the FFSI are described in an article by Schroeder et al. in the *Journal of Hydrology.*

**Interpretations of flood return periods.** Based on the varying interpretations of flood return periods even among the workshop participants who are generally familiar with this topic, an experiment was designed to examine how these concepts are understood by the broader populace. Jared LeClerc, a Ph.D. candidate in psychology at the University of Washington (who has since completed his degree), conducted an exploratory study to address some of these research questions. The study presented three different expressions of the flood risk to the participants, in the context of a monument similar to the one at Spring Creek in Fort Collins, but for a fictional location (“Bison City”). The first expression used return periods like those actually on the Spring Creek monument: 10-year flood, 100-year flood, etc. The second used percentages to represent the same risk: a 10% chance of happening in a given year, a
1% chance, and so on. The third expression was neutral, with letters (A, B, C, etc.) corresponding to the different levels of risk. The study also aimed to learn whether people's interpretation of the flood risk would be affected by the recency of a flood at that location.

For example, one question on the survey asked “How likely do you think Bison City is to experience a flood this year?”, with different participants being given the return-period expression of risk, the percent expression, and the neutral expression, and with some participants told that a flood occurred the previous year, and others told that Bison City had not seen flooding in about 10 years. For those given the percentage expression of risk (i.e., a 1% probability of occurring in a given year), there was no significant difference in the participants perception of the likelihood of experiencing a flood this year between those who were told that a flood had and had not occurred recently. On the other hand, for the participants given the return period expression of risk (i.e., a 100-year flood), those who were told that a flood occurred the previous year rated the risk of flooding this year lower than those who were told that no flooding had occurred in 10 years. In other words, the hypothesis was supported that discussing a “100-year flood” leads people to believe that when one such flood occurs, another will not happen again for a long time. This research was exploratory and was limited by a relatively small sample size, but nonetheless raises questions for future research at the interface of meteorology, hydrology, and society.

**Other research projects.** The projects highlighted above reflect only a small subset of the projects initiated at or inspired by the workshop. A couple of additional projects are summarized below:

- Ben Miller (economics, University of California, San Diego) examined the economic value of weather warning systems such as NOAA weather radio.

- A multidisciplinary group is examining weather events that include multiple hazards, such as a near-concurrent threat of tornadoes and flash floods, along the lines of what occurred in the El Reno/Oklahoma City area on 31 May 2013. Components of this research led to an article that was published in *Weather and Forecasting* in 2015.

Furthermore, numerous students reported being motivated to take courses outside their primary discipline and completing class research projects that incorporated interdisciplinary approaches.

**FEEDBACK, DISCUSSION, AND REFLECTION.** Feedback from the student participants was very positive, with many stating that it provided new ways of looking at scientific and societal issues related to flooding. For example, one student noted, “One of the strong points of the workshop was how it opened my eyes to how other fields look at flood events,” and another commented that they left the workshop feeling “reinvigorated and optimistic about doing good science.”

However, one theme that ran through some of the student feedback was that efforts to integrate the physical and social sciences can still leave a disconnect between the two lines of inquiry. For example, whereas most of the physical scientists felt that they learned a lot about the research methods offered by the social sciences (e.g., “I have so much more insight into the social science perspective and methods after this workshop”), some of the social scientists found it challenging to be truly integrated members of the research team (e.g., “I think that the social scientists still had difficulty getting their perspectives represented in the final group projects”). This suggests that even though efforts (including this workshop) to integrate the methods, approaches, and “languages” of the different sciences have largely been successful, there remain challenges to overcome in the future. These challenges were a major topic of discussion during the second meeting of the workshop in 2014—particularly how to highlight interdisciplinary experience and interests during the job search process.

Before the initial workshop, a Facebook group was organized for the participants in the workshop to post relevant articles, job opportunities, and topics for discussion. This group remained active through the 2013 and 2014 workshops, and continues to be a place where the participants keep in touch to share information about their progress through graduate school or their new careers, publication of journal articles, and current flood-related information. In addition to this virtual communication, we have organized a SPREAD lunch or dinner at each of the AGU and AMS Annual Meetings since the workshop so that those attending the meetings can reconnect.
Overall, the SPREAD workshop brought together graduate students at the cutting edge of research on extreme precipitation and floods, highlighting the inherently multidisciplinary nature of floods along with the opportunities for solving scientific and societal problems that come with applying diverse academic methods and perspectives. The workshop resulted in several fruitful research activities that will advance understanding of precipitation and flooding. Even more importantly, the workshop fostered the development of a network of early-career researchers and practitioners who will be “multilingual” in terms of scientific disciplines, and who are poised to lead both within their respective careers and across the scientific community.

ACKNOWLEDGMENTS. The SPREAD workshops were supported by NSF grant AGS-1157425. Thanks to all of the participants in the workshop, and to all of the speakers and presenters. Special thanks to Jared LeClerc, Jen Henderson, JJ Gourley, three anonymous reviewers, and editor Greg Byrd for providing constructive feedback that helped improve this manuscript. The efforts of Matt Kelsch in leading the tour of Front Range flood locations in both 2013 and 2014 are appreciated immensely. Thanks also to Clark Evans for suggesting the “SPREAD” name for the workshop, and to Karrie Butler of Colorado State University for organizing all of the logistics for the workshops in both 2013 and 2014.

FOR FURTHER READING


A blue-sky approach to understanding cloud formation

by Ben Slater, Angelos Michaelides, Christoph G. Salzmann, and Ulrike Lohmann

Recent developments in our basic understanding of ice nucleation are discussed that highlight the transformative potential of allying experiment, field measurement, and theory.

Clouds directly influence the planetary albedo and thermal radiation in opposite ways, and they hence largely determine the radiative energy budget of Earth, impacting the global temperature, weather, and society. However, understanding the factors that influence ice formation within clouds is a major unsolved and pressing problem and an important missing piece in our understanding of past, present-day, and future climate that is highlighted in the 2013 Intergovernmental Panel on Climate Change report (Boucher et al. 2013). Here, we outline recent breakthroughs that have significantly advanced our understanding of the field. These developments lead us to suggest that now there is an opportunity to make substantial progress toward understanding ice formation in the atmosphere. We argue that a concentrated effort should be dedicated to studying mimic/proxy materials, utilizing an array of investigative tools that span from the nanometer scale to cloud chamber experiments and atmospheric observations.

Crystallization of water is such a familiar process that one might presume that by the twenty-first century, the basic mechanism by which water freezes or “nucleates” into ice is well understood. However, water continues to reveal unexpected properties, such as that ice nucleates at different rates on oppositely charged plates of a pyroelectric (Ehre et al. 2010), a phenomenon that may be relevant to triboelectric charging (electrification of ice particles due to friction upon collision) in clouds and is yet not understood. Residues obtained from cloud ice crystals are dominated by mineral dust and biological particles (Pratt et al. 2009; Cziczo et al. 2013; DeMott 2003; Twohy and Poellot 2005), suggesting these species are important for ice formation. A key question in cloud formation then is what makes good ice nuclei? Although it has been known for decades that dust of
various origins, bacteria, fungal spores (O’Sullivan et al. 2015; Hoose and Möhler 2012), and other biological particles, such as cellulose (Hiranuma et al. 2015) and diatom-infused sea spray (Wilson et al. 2015), can raise the nucleation temperature, a molecular-scale picture of why materials of disparate chemical composition and structural order can have similar ice nucleation efficiency is lacking. Recently, there seems to have been a breakthrough by Atkinson et al. (2013) who reported that K-feldspar (where K$^+$ is a countercation to the negatively charged alumino-silicate framework), a component in Saharan Desert dust, is an exceptionally potent ice nucleator (IN), inducing crystallization in otherwise pure water at around −15°C, more than 20°C above the temperature of spontaneous crystallization of pure water. Figure 1 shows the results of a dust-modeling study parameterized on desert dust sample data that shows feldspar concentration and ice nuclei distribution centered on the Saharan region; feldspar is predicted to be a major contributor to observed IN densities.

The reasons for the exceptional potency of K-feldspar, metallic particles (Cziczo et al. 2013), and other very efficient ice nuclei, such as commercially marketed silver iodide and bacteria, to control cloud, ice, and snow formation are not clear. The classic textbook treatment of this topic (Pruppacher and Klett 1997) identifies five ingredients for an efficient IN: 1) insolubility, 2) size (potent ice nuclei are observed to be larger than the critical nucleus diameter of ice; this diameter depends on temperature), 3) chemical bonds (surface-accessible hydrogen bond acceptor/donor groups), 4) crystallographic match (the IN surface should have a close geometric match with one of the principal crystal growth planes of ice), and 5) active sites (experimentally it is observed that only

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**Fig. 1.** The remarkable correlation between (a) dust particulate density, (b) feldspar density, and (c) ice nuclei density, concentrated over the Saharan region. (d) The good correlation between modeled and observed ice nuclei density over a 10-K temperature range. [Taken from Atkinson et al. (2013).]
a fraction of available surface area initiates crystallization; see also Fig. 2, taken from Thürmer and Nie (2013). Discriminating, for example, the role of bonding from crystallographic match and determining the structure of active nucleation sites and then assessing their importance in different atmospheric conditions requires a systematic, multipronged, and concerted approach. Although materials such as feldspars are very potent ice nuclei, their structures are a challenge to characterization and atomistic modeling approaches because of their complex chemical composition and low structural symmetry. A model material is clearly needed that is amenable to study by nanoscale modeling, microscopic and spectroscopic methods, and cloud chamber experiments, has IN potency, and hence is relevant to atmospheric observations. Quartz (SiO$_2$), for example, satisfies these criteria; it is a major component of desert dust [e.g., 16% (Atkinson et al. 2013)], it is a potent IN (e.g., Atkinson et al. 2013), and its structural chemistry is more tightly constrained than feldspar and clay minerals.

Although there is mounting data on the efficacy of different types of ice nuclei, one of the biggest gaps in our knowledge today is the scarce atomic-scale characterization data of IN active materials. In the case of IN minerals, what is the shape (as well as size) of the IN crystal? What faces are expressed? Does the aspect ratio (relative size of different crystal faces) of an IN affect potency? Are point defects (e.g., ion vacancies) and line defects (e.g., growth spirals) key “active sites” that trigger crystallization of ice? To begin to answer these questions, we need an array of spectroscopic techniques, including high-resolution confocal laser microscopy to identify surface topography (e.g., Sazaki et al. 2010), allied with atomic force microscopy and scanning tunneling microscopy (Fig. 2) to identify and establish how IN potency correlates to structural features. The latter techniques can be used to examine atmospheric and test dust samples, but other techniques can probe in situ interfacial structure directly. A recent study (Lis et al. 2014) beautifully illustrates how sum-frequency generation experiments can discern distinct structural layers at a SiO$_2$–water interface, showing that the bulk liquid flow rate of the water across the surface affects the water structure at the interface. Catalano (2011) has used small-angle x-ray scattering techniques to observe the layering of water at the corundum–water interface, which has recently been confirmed through novel atomic force microscopy and computer simulation studies (Argyris et al. 2013). Interestingly, the layering of water at interfaces has been phenomenologically linked to facilitating the nucleation of ice on sootlike and graphene nanoflakes (Lupi et al. 2014) and kaolinite (Cox et al. 2013) films according to nanoscale molecular dynamics simulations but the mechanism [and its generality (Cox et al. 2015a,b)] has yet to be extricated. Experimental in situ probes provide a way of examining how highly oriented deposited or grown substrates affect water at the interface, which can be compared and contrasted with experiments on distinct crystallographic faces of natural dust samples. Similarly, the nucleation efficiency of materials with identical nominal stoichiometry but different aspect ratio and step density can be compared in cloud chamber experiments (e.g., Hiranuma et al. 2014). Surface characterization methods and in situ spectroscopies provide a valuable feedback mechanism to nanoscale modeling. Atomistic modeling can be used to construct structural features on materials to assess whether, for example, growth spirals or steps accelerate or inhibit ice crystallization and the prediction cross referenced with in situ measurements and cloud chamber experiments.

The predictive capability of nanoscale modeling approaches has grown rapidly in the last few years and there have been a number of notable discoveries relevant to understanding the nucleation mechanism...
in ice. Moore and Molinero (2011b), Li et al. (2011), and Sanz et al. (2013) have reported on detailed studies of homogenous ice nucleation, yielding estimates of the size of the critical nucleus as a function of temperature that compare well with those obtained experimentally. Moore and Molinero also showed evidence that as the homogenous nucleation temperature of approximately −41°C is approached, a rapid increase in the tetrahedrality and four-coordinated water molecules is observed and that extended patches of structured water are crucial for stabilizing critical nuclei. A vivid example of the predictive capability of simulation approaches can be seen in the work on the detailed structure of ice embryos, where supercooled water was shown to contain crystallized ice with sequences of hexagonal and cubic ice (Moore and Molinero 2011a). Consistent with those observations, a concerted study involving crystallization experiments, x-ray diffraction analysis, and direct computer simulation of crystallization showed that what has historically been referred to as cubic ice is in fact a stacking disordered ice structure I_{sd} consisting of sequences of cubic and hexagonal stacking (Fig. 3; Malkin et al. 2012; Kuhs et al. 2012). Because I_{sd} is metastable with respect to hexagonal ice, its vapor pressure is higher and hence its activity in cloud microphysics is distinct from hexagonal ice.

There have been transformative breakthroughs in recent years in understanding the structure of supercooled water (Sellberg et al. 2014; Moore and Molinero 2011b) and the mechanism of crystallization of ice (Malkin et al. 2012; Moore and Molinero 2011a); developments in microscopy to follow in situ ice crystallization on model dust materials (Thirmer and Nie 2013; Sazaki et al. 2010); instruments capable of measuring all modes of the ice nucleation cycle, including techniques for measuring tropospheric water vapor concentration (Neely and Thayer 2011); methods of characterizing the structure of ice in clouds (Carr et al. 2014); the composition of cirrus clouds (Cziczo et al. 2013); the elucidation of aviation-induced contrail and cirrus formation (Burkhardt and Kärcher 2011); models that probe cloud microphysics, including supersaturation variability and its influence on ice nucleation (Kärcher et al. 2014); and the revelation of minor components in aerosol particles, which have a major influence on ice nucleation (Atkinson et al. 2013; Cziczo et al. 2009). With these developments in experimental techniques, modeling approaches, and the capability to simulate cloud microphysical processes in cloud chamber facilities such as the Aerosol Interaction and Dynamics in the Atmosphere facility (www.imk-aaf.kit.edu/73.php), there is an unprecedented opportunity to tackle the long-standing problem of ice nucleation in clouds. We suggest that a coherent study on an agreed set of materials would help to accelerate the rate of discovery in this area and bridge the gap between the atmospheric science community and materials science approaches. Model dust materials, such as quartz, are accessible to atomistic modeling approaches, state-of-the-art surface science, and characterization techniques, as well as crystallization and cloud chamber experiments. We believe that a combination of approaches is necessary to untangle cloud microphysical processes from the details of IN microstructure and their relative importance on ice and cloud formation and, ultimately, climate.

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![Fig. 3. A nucleus of stacking disordered ice at −53°C, revealing an irregular sequence of hexagonal (green) and cubic (cyan) stacking. A pure cubic form of ice has never been experimentally isolated (Malkin et al. 2012).](image-url)
REFERENCES


A SIGHT FOR SORE EYES
The Return of True Color to Geostationary Satellites

by Steven D. Miller, Timothy L. Schmit, Curtis J. Seaman, Daniel T. Lindsey, Mathew M. Gunshor, Richard A. Kohrs, Yasuhiko Sumida, and Donald Hillger

Japan’s Himawari-8 Advanced Himawari Imager enables use of the first true-color imagery from the geostationary orbit in nearly half a century and previews advanced capabilities of the next-generation international constellation.

The old adage goes that “a picture is worth a thousand words.” When it comes to pictures taken of Earth from the vantage point of space, these words ring especially true. Iconic examples include the “Earth rise” over a lunar foreground, captured by the crew of Apollo 8 in December 1968, and the “Blue Marble” taken by the crew of Apollo 17 in December 1972. They reveal to our eyes a strikingly colorful, dynamic, and borderless world—one whose form and function as a kind of living, breathing organism can only be realized from the holistic view. From afar, the Blue Marble conveys a peaceful and unifying message of “home” to a world embroiled in unrest and division.

Practically speaking, imaging radiometers provide a unique dual perspective on Earth’s complexity and connectivity. In the most basic sense, the “eyes” of satellite radiometers collect energy in the form of photons impacting a detector—the more energy received, the higher the digital count value. These counts are converted into Earth-located measurements of reflected sunlight and thermal emission. This quantitative information resides at the spatial granularity of picture elements, or pixels, collected via scan patterns that vary with satellite orbital configuration and instrumentation. When considered at the pixel level, the data offer an ability to quantify the properties of the surface and atmosphere at a discrete viewing location. When displayed as georeferenced (or mapped) imagery, we are able to visualize how each pixel’s information fits within the spatial context of the whole scene. These two forms of information content—quantitative products and qualitative context—are fully complementary and inseparable attributes of satellite data.

Satellite imagery comes in many forms—from simple, single-band images for a specific spectral...
range to more sophisticated (and higher information content) multispectral-band combinations rendered via red–green–blue “false color” composite techniques (d’Entremont and Thomason 1987). Among the latter, the special case of “true color” is perhaps the single most familiar and visually intuitive form of multispectral satellite imagery (Miller et al. 2012). True to its name, true color combines appropriately scaled red-, green-, and blue-band reflectance values to form imagery that approximates the response of normal human photopic (daytime) vision. In essence, true color mimics what we see with our own eyes, producing an image reminiscent of color photography.

When it comes to daytime interpretation of surface and atmospheric properties, true-color imagery offers distinct and practical advantages. With true color, the oceans appear blue, shoals and coastal waters are turquoise, the forests are green, and the deserts are tan. In panchromatic visible imagery, the millions of colors perceptible by normal human vision (Chapmanis 1954) are reduced to roughly 40 discernible shades of gray. Thus, atmospheric features such as clouds, dust storms, volcanic ash, and smoke/pollution are confined to a very limited grayscale range instead of the more familiar and readily distinguishable whites, yellows, dark browns, and bluish grays seen in true color. While it is often possible to distinguish these various features through crafing of multispectral algorithms displayed as false-color imagery enhancements (e.g., Miller et al. 2006a), mastering the interpretation of such imagery often requires dedicated training and time in hands-on experience. True color appeals to our “intuitive interpretational skillset” in this regard—our inherent familiarity with the color space of the world as we perceive it with our own eyes.

Despite the clear appreciation and seemingly insatiable appetite for high-quality and visually intuitive satellite imagery among the circles of Earth science research, public/private weather forecasting sectors, and the general public alike, we have operated for the past 50 years without a requirement for true-color imagery on our geostationary (GEO) “imaging” sensors. Not since the very dawn of the meteorological satellite era, for a brief stint on NASA’s Applications Technology Satellite 3 (ATS-3) satellite in 1967 (Suomi and Parent 1968; Warnecke and Sunderlin 1968), has a GEO-based sensor offered such a capability. Given the realities of limited satellite program budgets, technical considerations related to focal plane array size, filter technology, and spatial/spectral resolution versus data transmission rate tradeoffs have driven careful prioritization of sensor requirements. Here, true color has been relegated to more of a luxury item rather than a mission-critical necessity.

Compelling arguments for true color do exist, including statements from the founding fathers of satellite meteorology. Suomi and Parent (1968) and Warnecke and Sunderlin (1968) point out some of the unique benefits and information content of the first true-color picture of Earth collected by ATS-3, contrasting it to the conventional grayscale panchromatic visible imagery also available at the time:

This picture is not only a new technology triumph but it reveals a large amount of meteorological information and demonstrates a tremendous potential for meteorological research and operations. A striking advantage over black-and-white photographs is the improved contrast of clouds against the background and the resulting higher effective resolution. Particularly over bright areas with a high surface albedo, color photography obviously permits a better and more detailed detection of cloud distribution and structure.

[…] The superiority of color photography is based on the ability to detect the color peak of the reflectance curve of the different natural objects like water, land, and clouds in addition to the integrated intensity, which is the only parameter detectable by black-and-white photography.

True color has existed for several decades on nonoperational low-Earth-orbiting (LEO) satellite platforms, with more widespread forecast community usage emerging with the launch of NASA’s Terra (1999) and Aqua (2002) polar-orbiting satellites [carrying the Moderate Resolution Imaging Spectroradiometer (MODIS)]. The National Oceanic and Atmospheric Administration (NOAA) Joint Polar Satellite System (JPSS), initiated by the Suomi National Polar-Orbiting Partnership (Suomi-NPP) introduced true-color capabilities to the operational program in late 2011 via the Visible Infrared Imaging Radiometer Suite (VIIRS). Global data from these LEO satellites have been made available to users in near–real time and typically provide superior spatial resolution to GEO observations.

There are distinct advantages and limitations to the LEO constellation in terms of coverage and refresh rate. The operational LEO programs, which typically fly in sun-synchronous orbits, provide 90–100-min temporal refresh (with some longer gaps interspersed) at high latitudes. This frequency enables numerous applications that are either unavailable or of superior quality to GEO. However, with these
same LEO satellites providing only about two local overpasses per 24-h period at mid- and low latitudes, opportunities to characterize the rapidly changing atmospheric state in these regions are more limited.

At these lower latitudes, the GEO platform takes on added importance. GEO imagery, having the inherent ability to provide rapid refresh rates (looping of imagery to discern motion and evolution of various parameters), is extremely valuable to operational forecasters. Several researchers have demonstrated the advantages to forecasters of high-temporal-resolution imagery and derived products (e.g., Purdom 1976; Schmit et al. 2013; Bedka et al. 2015; Schmit et al. 2015). Here, the regular sampling interval and fixed viewing geometry of the GEO platform complements and augments the detailed information provided by LEO satellites.

The satellite community took “one giant leap for imagery-kind” with the launch of the Japan Meteorological Agency’s (JMA) Himawari-8 on 7 October 2014. Himawari (Japanese for “sunflower”) is the first of the next generation of GEO satellites, with forthcoming members of this international constellation over the next decade to include NOAA’s Geostationary Operational Environmental Satellite R-Series ([GOES-R], carrying the Advanced Baseline Imager (ABI), e.g., Schmit et al. (2005)), the Korea Meteorological Administration (KMA) Geostationary Korea Multipurpose Satellite 2A ([Geo-KOMPSAT-2A], carrying the Advanced Meteorological Imager (AMI)), the China Meteorological Administration (CMA) Feng Yun-4 ([FY-4), carrying the Advanced Geosynchronous Radiation Imager (AGRI)], and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Meteosat Third Generation ([MTG], carrying the Flexible Combined Imager (FCI)). The 16-band Advanced Himawari Imager (AHI; built by ITT Exelis, now a part of Harris Corporation) on Himawari-8 features many of the spectral imaging capabilities traditionally relegated to the LEO platform. Thus, AHI represents an important initial test bed for development of applications that can be passed along to other members of the new global constellation.

Here we summarize early developments and present initial results for atmospherically corrected true-color imagery from Himawari-8 AHI. In particular, we detail an adjustment made to AHI’s 0.51-µm native “green” band that enhances the ability to identify green vegetation and provides a more consistent appearance with respect to legacy polar-orbiting true-color imagery products.

**THE HIMAWARI-8 ADVANCED HIMAWARI IMAGER.** JMA commissioned the Himawari-8 GEO satellite to operational status on 7 July 2015 (Bessho et al. 2016). The satellite subpoint for Himawari-8 is 140.7°E, hovering over the equatorial region just north of Papua New Guinea and providing a wide ranging view of the western Pacific. The AHI is a state-of-the-art optical spectrum radiometer that acquires multispectral images at high frequency: 10-min sampling of full-disk imagery and 2.5 min for regional imagery (collected over Japan and other ephemeral targets of high interest to forecasters, such as typhoons or volcanic eruptions). It includes 3 visible-spectrum (VIS) bands, 3 near-infrared (NIR) bands, and 10 thermal-infrared (IR) bands. The spatial resolutions of these bands are approximately 4 times improved over their counterparts on JMA’s heritage Multifunctional Transport Satellites (MTSAT) series imagers.

For interests of this work, we begin by considering the VIS and NIR bands at wavelengths below 1 µm. Table 1 compares response functions and spatial resolutions of the heritage LEO (MODIS and VIIRS) and next-generation GEO (AHI and ABI) sensors for specific bands of focus. While the red- and blue-band

<table>
<thead>
<tr>
<th>Band name</th>
<th>MODIS</th>
<th>VIIRS</th>
<th>AHI</th>
<th>ABI</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>FWHM (µm)</td>
<td>Res (km)</td>
<td>No.</td>
<td>FWHM (µm)</td>
</tr>
<tr>
<td>Blue 3</td>
<td>0.459–0.479</td>
<td>0.5</td>
<td>M3</td>
<td>0.478–0.488</td>
</tr>
<tr>
<td>Green 4</td>
<td>0.545–0.565</td>
<td>0.5</td>
<td>M4</td>
<td>0.545–0.565</td>
</tr>
<tr>
<td>Red 1</td>
<td>0.620–0.670</td>
<td>0.25</td>
<td>M5</td>
<td>0.662–0.682</td>
</tr>
<tr>
<td>NIR 2</td>
<td>0.841–0.876</td>
<td>0.25</td>
<td>M7</td>
<td>0.846–0.885</td>
</tr>
</tbody>
</table>
response functions show minor differences between MODIS/VIIRS and AHI, the green is the only band without overlap—an important point that we shall revisit later. Figure 1 shows the spectral response functions for the sub-1-µm bands of AHI, providing the blue–green–red bands used for true-color imagery as well as the 0.86-µm band (often referred to as the “vegetation band” for its strong sensitivity to chlorophyll content, and hence its principal use in monitoring vegetation health). For reference, reflectance data for healthy grass and barren/desert sand taken from NASA’s Advanced Spaceborne Thermal Emission and Reflection (ASTER) spectral database are also shown (Baldridge et al. 2009).

**TRUE-COLOR PROCESSING WITH RAYLEIGH CORRECTION.** Rendering high-quality true-color imagery from AHI entails preprocessing of the blue, green, and red (AHI bands 1, 2, and 3) VIS reflectance data for reduction of scattering contributions from the molecular (or Rayleigh; e.g., Young 1981) atmosphere. As Rayleigh scattering efficiency is nonlinearly proportional to inverse wavelength (i.e., \( Q_s \sim \lambda^{-4} \)), the atmospheric component of the signal is considerably more noticeable for shorter wavelengths (on AHI, most notable in the 0.47-µm blue band). Without reduction of this signal, true-color imagery will take on a milky blue appearance, particularly near the horizon where the viewing path through the atmosphere is long. These adjustments are referred to hereafter as atmospheric “corrections,” done to produce a crisper/cleaner version of true-color imagery.

For AHI Rayleigh corrections, we have modified the software of NASA SeaDAS ([http://seadas.gsfc.nasa.gov/](http://seadas.gsfc.nasa.gov/)), a radiative transfer modeling package designed initially for ocean color retrievals. There is no account in the current approximation for aerosol or spatial variations in atmospheric species and pressure. The changes entailed modifying atmospheric absorption parameters, updating the band-integrated solar irradiance, and computing new lookup tables of view and illumination geometry-dependent Rayleigh scattering reflectance corresponding to AHI spectral bands 1–4. The scattering corrections require knowledge of solar and satellite zenith and relative azimuth angles at each pixel. These values are precalculated as a function of image collection date and time. The Rayleigh component is subtracted from the observed reflectance, and this difference is normalized by the atmospheric transmittance for the sun–Earth–satellite photon path. The Rayleigh-corrected reflectance values are then scaled log linearly to mimic the nonlinear response of human vision and generally brighten the true-color imagery.

There were some additional adjustments needed to accommodate challenges specific to full-disk imagery. The first dealt with the model’s assumption that the atmospheric path always reaches the surface. To avoid overcorrection of pixels at high satellite zenith angles, where high/thick clouds significantly reduce the photon optical path through the atmosphere compared to clear sky, the Rayleigh component was reduced by a factor scaling with cloud-top height (here, using cold AHI 10.35-µm brightness temperatures as a proxy for high clouds). Second, as the correction breaks down nonlinearly at very long atmospheric pathlengths near Earth’s limb, uncorrected reflectance data are blended in gradually from satellite zenith angles of 75°–85°, carrying on as uncorrected out to the edge of limb. These measures are taken for cosmetic purposes, and they affect a small fraction of the full-disk imagery.

Figure 2 shows uncorrected and atmospherically corrected full-disk AHI true-color imagery for 0230 UTC 25 January 2015—working in this case...
on the first AHI test data made publicly available by JMA. The impact of the atmospheric correction on image sharpness and the general ability to discern land surface features is readily apparent. Optimized coding has enabled end-to-end production of full-disk imagery in roughly 7 min (using a desktop computer running Linux, equipped with 24 GB of RAM and a 6-core Intel Xeon W3690 CPU), meaning that 10-min AHI full-disk true-color imagery can currently be processed in real time. Smaller domains require a commensurately smaller fraction of time, such that processing of storm-scale rapid scan sectors should remain computationally tractable.

**ANALYSIS REVEALS AN APPARENT ISSUE WITH THE NATIVE AHI GREEN BAND.** Upon closer inspection of Fig. 2b, it becomes evident that the visual appearance of certain land surfaces deviates from the true-color imagery produced by legacy sensors on the LEO satellites mentioned above. Figure 2c shows the MODIS Blue Marble dataset matched approximately to AHI coverage—taken here as the qualitative standard for expected cloud-free true-color appearance. Comparing Figs. 2b and 2c, we notice that vegetation over the tropical Maritime Continent appears “too brown,” while the Gobi desert and some parts of the Australian Outback are “too red.” The deviations are explained in both cases by suppression of the green-band component in the RGB composite. Given that AHI’s green band was designed to capture green signals explicitly in support of a native true-color imaging capability—the disparity warrants closer inspection.

After confirming that no obvious errors resided in the atmospheric correction code, we turned our attention to the spectral response function of the AHI green band. Figure 3 hones in on the AHI green-band segment of Fig. 2, showing its placement in comparison to the VIIRS moderate-resolution band 4, a 0.55-µm band used in Suomi-NPP true-color imagery, and similar to Terra/Aqua MODIS band 4. Also overlaid on Fig. 3 is the chlorophyll signal of healthy green vegetation (extracted from the ASTER spectral library). It is readily apparent that AHI’s

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**Fig. 2.** Example of AHI full-disk true-color imagery (0230 UTC 25 Jan 2015) (a) without atmospheric correction, (b) with corrections applied, and a subset of MODIS Blue Marble dataset for a domain containing much of AHI’s field of regard.
green band, while in the green part of the spectrum, is not aligned optimally with the local peak of a typical VIS-spectrum green vegetation reflectance signal. The relative blue shift explains both the suppression of green vegetation and the appearance of redder barren soils (owing to strong absorption by silicates; e.g., Patterson et al. 1977) when comparing AHI true color to the MODIS Blue Marble. Whereas the red and blue-band response functions also differ slightly between MODIS/VIIRS and AHI, unlike the green band they do overlap (Table 1). More importantly, there are not strong, localized, and nonmonotonic spectral variations of surface properties in the blue and red that would be accentuated by differences in the response functions, as seen with chlorophyll signal in the green band.

At this point, it is worth mentioning that by definition true-color images use information only from the current observations and do not rely on ancillary base maps for depicting the land–ocean surface background. Given the lack of the requisite spectral bands for true-color imagery, one approach to approximate true color using data from the current GEO imagers is to use a color base map (sometimes produced from MODIS Blue Marble data; e.g., Miller et al. 2006b) and then overlay the currently observed clouds. While colorful, this approach will not represent as well any short-term surface changes, such as burn scars, vegetation, and water turbidity, that were not present at the time of the base-map compilation. Additionally, subtle atmospheric features, such as thin smoke and cirrus, may be missed more often when merging the current imagery with the base maps if thresholds are not selected carefully and dynamically.

**A HYBRID GREEN SOLUTION.** Based on the above analysis, addressing the deficiencies of the native AHI green band would require a nonuniform enhancement of the green signal over certain scene types. A uniform boost to the green reflectance would impart an unrealistic green tint to the imagery, particularly noticeable in the cloud field. Fortunately, a mitigating solution exists within the native AHI spectral suite. Inspecting AHI’s 0.86-µm vegetation-band spectral response function, shown in Fig. 1, we note that both desert and vegetation reflectance are high compared to the AHI green band. True to the band’s nickname, the vegetation signal increases from roughly 5% to 50% (strong chlorophyll-A reflectance), but sandy/loam soils’ signal increases as well—from about 15% to 35% (reduced silicate absorption). Clouds scatter uniformly across the VIS/NIR region, while water bodies are strongly absorbing. As such, AHI band 4 (0.86 µm) provides a boost to signals in exactly those areas where band 2 (0.51 µm) is green deficient, while maintaining a consistent signal in other areas.

With these considerations in mind, we proposed a modification to the AHI native green band—introducing a small fraction of the AHI vegetation-band reflectance to form a hybrid green band that “boosts” the signal selectively over green vegetation and barren desert surfaces. The fractional contribution \( F \), which assumes a fixed value between 0 and 1, blends the AHI green and vegetation bands in the following way:

\[
\text{hybrid green} = (1-F) \times R(0.51 \mu m) + F \times R(0.86 \mu m),
\]
Fig. 4. Comparison of true color imagery collected on 5 November 2015 over the Thailand region for (a) Suomi-NPP VIIRS (0617 UTC), (b) AHI native band reflectance (0620 UTC), (c) the RMSE minimization to determine hybrid green blending factor F, and (d) AHI with hybrid green version of this same scene using a 7% blend of the AHI 0.86 μm vegetation band.

Fig. 5. Comparison of true-color imagery collected on 7 Aug 2015 over the Australian region for (a) Suomi-NPP VIIRS (0408 UTC), (b) AHI native-band reflectance matched to this same scene (0410 UTC), and (c) corresponding AHI hybrid green version using a 7% blend of the AHI 0.86-μm vegetation band.
where \( R \) is the reflectance at the indicated spectral bands.

By definition, the bounds of \( F \) preserve either the native AHI green band (\( F = 0.0 \)) or the vegetation band (\( F = 1.0 \)), while values in between yield a blend between the two. Selection of an optimal \( F \) was done experimentally, using VIIRS M4 band (0.555 \( \mu m \)) as a benchmark. Using space–time matched VIIRS imagery, we varied \( F \) until the root-mean-square error (RMSE) between the AHI hybrid green and the VIIRS green reflectance data (both Rayleigh corrected) was minimized. This exercise converged upon a blend factor of \( F = 0.07 \), or roughly a 7\% incorporation of the 0.86-\( \mu m \) band, for optimal matching with VIIRS. Figure 4 shows the results for an example over Thailand. Given the strong response of the vegetation band, only a small contribution is necessary to achieve an acceptable result. As with any enhancement, selection of \( F \) can be tailored to suit specific user needs. At full-disk imagery scale, slightly higher values of \( F \) (up to about 0.15) can be used to further accentuate vegetation-dense regions. However, it was found that values higher than \( F = 0.20 \) produced large RMSE and the anomalous greening of deserts.

Figure 5 shows another comparison between AHI (uncorrected green band in Fig. 5a, hybrid green in Fig. 5b) and VIIRS (Fig. 5c) for closely matched, Rayleigh-corrected observations over Australia, using \( F = 0.07 \). Notable areas of increased green vegetation over Indonesia, Papua New Guinea, and parts of northern and eastern Australia improve the visual agreement with the VIIRS reference imagery. The crossover of vegetation and sand reflectance between 0.51 and 0.86 \( \mu m \) (Fig. 1) suggests that a spatially invariant blend factor \( F \) in Eq. (1) will necessarily impart a stronger enhancement to vegetation than to deserts. Figure 5 suggests that the visual effects of this disproportionate adjustment are slight, with the benefits outweighing the physical limitations of this simple approach. It is also evident that coastal waters, which may contain shades of turquoise/green depending on bathymetry (shallow waters) and turbidity (northern coast of Australia in Fig. 5), are not affected significantly by the hybrid green technique. For these scene types, their green tonality arises from the spectral mixing of broad reflectance signatures rather than a narrowband increase in green reflectance near 0.55 \( \mu m \) due to chlorophyll-A. This is why these coastal waters still appear as green/turquoise, and not brown like the vegetation, in the native AHI true-color imagery of Fig. 5a. While the agreement is not perfect, the hybrid approach appears to capture to first order the appearance of legacy true-color products.

Figure 6 shows the end product of the AHI processing detailed above. We refer to this approach as “hybrid, atmospherically corrected” (HAC) true color. As mentioned previously, a slight blend of uncorrected AHI data are introduced near Earth’s limb to provide better consistency with respect to the MODIS and VIIRS Blue Marble imagery, while also covering exponentially growing errors in the Rayleigh correction at long optical paths through the atmosphere. With Rayleigh correction and a dynamic boost applied to the green band, AHI’s captures our planet in the same colorful splendor as versions composited from polar-orbiting satellite sensors, but for the first time as a single contiguous image with an ability to animate at 10-min intervals over the full disk, and as often as every 2.5 min over target areas. When animated at the scale of full-disk imagery, the cloud and aerosol patterns (now readily distinguishable via true color) appear to evolve smoothly at this temporal resolution.

**A SIMPLE HYBRID, CONTRAST-STRETCH TECHNIQUE.** The simple hybrid contrast-stretch (SHCS) approach is a middle-ground solution for preparing true-color imagery that is “cleaner” than a direct combination of the red–green–blue AHI bands, but without incurring the computational burden of atmospheric corrections required by the
HAC approach. Here, each of the color components is stretched to suppress the atmospheric signal that HAC attempts to remove explicitly. The uncorrected reflectance data ($R_{\text{orig}}$ %) are first expressed in terms of 8-bit integer scaling, where 0 represents the minimum reflectance ($R_{\text{min}}$) and 255 represents the maximum reflectance ($R_{\text{max}}$) of the scaling bounds. For the current examples, we have set $[R_{\text{min}}, R_{\text{max}}]$ to $[0, 125]$% for all three (red, hybrid green, and blue) AHI bands. Values higher than 100% on the upper bounds of this range accommodate three-dimensional effects such as the side illumination of clouds. The following approach is used to conduct this 8-bit integer scaling:

$$R_{\text{new}} = 255 \times \frac{R_{\text{orig}} - R_{\text{min}}}{R_{\text{max}} - R_{\text{min}}} \quad (2)$$

These scaled reflectance are then rescaled piecewise linearly over three predefined ranges, shown in Table 2. This rescaling follows the same general construct as Eq. (2) (but without the 255 premultiplier).

For SHCS, the AHI hybrid green band uses $F = 0.13$ to attain optimal color matching with the legacy MODIS/VIIRS green band. The rescaled bands are then combined to form the SHCS true-color imagery. The minimum values used for restretching were determined empirically, based on a relatively small set of sample data, and therefore may require fine tuning as a function of season, location, and time of day.

The net effect of the SHCS rescaling is to increase the dynamic range of the midrange reflectance values at the expense of the low- and high-end ranges. The method achieves a pseudo-Rayleigh correction by applying successively stronger low-end

<table>
<thead>
<tr>
<th>Band name</th>
<th>Original scaling range</th>
<th>Rescaled range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>[0, 47] [47, 116] [116, 255]</td>
<td>[0, 12] [12, 138] [138, 255]</td>
</tr>
<tr>
<td>Hybrid green</td>
<td>[0, 38] [38, 107] [107, 255]</td>
<td>[0, 13] [13, 130] [130, 255]</td>
</tr>
<tr>
<td>Red</td>
<td>[0, 33] [33, 100] [100, 255]</td>
<td>[1, 14] [14, 124] [124, 255]</td>
</tr>
</tbody>
</table>

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Fig. 7. Comparison of AHI true-color imagery based on (a) the SHCS method [$F = 0.13$; per Eq. (1)] and (b) the HAC method ($F = 0.07$) for full-disk imagery collected at 0330 UTC 7 Jul 2015. A string of three tropical storms seen churning over the western Pacific Ocean are, from approximate image center to eastern limb, Typhoon Chan-hom, Typhoon Nangka, and Tropical Storm Linfa. Animations of this example for uncorrected, SHCS, and HAC true-color imagery are available at http://dx.doi.org/0.1175/BAMS-D-15-00154.2.
suppressions for the green and blue bands. Figure 7 compares the SHCS approach against the fully corrected (HAC) AHI imagery for full-disk AHI imagery, collected at 0330 UTC 7 July 2015. This particular date holds the distinction of being the official operational commissioning of Himawari-8. A video of the HAC method for this date is included in the online supplement for this article (available online at http://dx.doi.org/10.1175/BAMS-D-15-00154.2).

Figure 8 hones in on a comparison of unaltered reflectance, SHCS and HAC true-color imagery for a zoomed-in region of northern Australia at 0300 UTC 11 August 2015. Both methods provide a visually superior result to native-band imagery through the suppression (either via scaling in the case of SHCS, or physical account via HAC) of the Rayleigh signal. When comparing the two methods, the main advantage of the SHCS approach is that it is very fast to process, having no Rayleigh corrections or attendant requirements for solar/satellite geometry information. An additional benefit of SHCS is that no processing artifacts from Rayleigh corrections are introduced near the terminator. The principal disadvantage is that SHCS will not appear as vivid as the HAC method in some areas and/or at certain times of day, since the molecular signal is in fact still present in all of the bands used. As a result, certain features such as thin smoke, water shoals/turbidity, and phytoplankton blooms may not stand out as readily as they do in HAC true-color imagery, particularly at more oblique view angles. It is possible that a time-dependent scaling of SHCS could improve performance, and this is an area of ongoing study.

ILLUSTRATIVE EXAMPLES. The benefits of true color for scene interpretation are best appreciated when honing in on specific examples at higher spatial resolution. Figure 9 highlights several examples of atmospheric aerosol originating from both natural and anthropogenic sources, as seen with AHI’s HAC true-color algorithm. Volcanic ash plumes may take on a variety of colors depending on the nature and composition of the ash plume (e.g., Yamanoi et al. 2008). In Fig. 9a, an explosive eruption of the Manam Volcano in Papua New Guinea produced a “mushroom” cloud with tan coloration. The ability to distinguish plumes of different constituents is highlighted in Fig. 9b, where the residual dark smoke from the Tianjin, China, industrial explosion stands out readily against the semipersistent grayish-blue haze of pollution in southeastern China. Looking toward the limb of AHI’s field of view, Fig. 9c shows massive smoke plumes billowing from a complex of Russian forest fires burning out of control near Lake Baikal, and Fig. 9d captures the advance of an expansive wall of desert dust meandering across the complex terrain of central China.

With the aid of true-color imagery, these varying features appear readily and distinctly from surrounding meteorological clouds. Includ-
ing the temporal dimension further assists in feature discrimination and interpretation. Videos corresponding to subpanels of Fig. 9 and the full-disk scene of Fig. 7, shown at various stages of true-color imagery enhancement ranging from no adjustments whatsoever (native-band reflectance), to SHCS, to the full HAC approach, are provided as online supplemental information to this article.

**DISCUSSION.** AHI’s green band was selected by JMA for the purpose of providing a native true-color imaging capability. The obvious question that arises from this discussion is why the band was positioned outside the green peak of the vegetation spectral reflectance spectrum? Personal communications between the authors and representatives of EUMETSAT and JMA may help to shed light on this question. During the scoping of Europe’s next-generation geostationary satellite imager, the MTG/FCI, EUMETSAT selected a 0.51-µm green band for aerosol property retrievals. This green was not aligned with the 0.55-µm chlorophyll-A structure, since its user base had not voiced a specific requirement for true-color imagery at that time. Subsequently, JMA adopted this 0.51-µm aerosol-centric green band for Himawari-8 AHI, but with the expectation that it would satisfy their requirements for true-color imagery. The KMA adopted the same EUMETSAT/JMA green band for Geo-KOMPSAT-2A AMI, also for the purposes of supporting true-color imagery. Whereas the underpinning requirement for the green band changed along the way, the corresponding green-band specification apparently did not.

It is worth noting that in the early design phase of the GOES-R ABI, a 0.55-µm band was proposed for the express purpose of supporting true-color imagery. In the design trade space considered for the 16-band sensor, only six reflected-solar bands could fit on the focal plane array. The requirement for subvisual cirrus detection drove selection of the 1.38-µm

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**Fig. 9.** A variety of atmospheric features whose interpretation is facilitated by HAC true-color AHI imagery: (a) volcanic ash plume from the Manam Volcano in Papua New Guinea (31 Jul 2015); (b) a dark smoke plume associated with the Tianjin, China, industrial explosions drifts with lighter-gray background pollution (12 Aug 2015); (c) biomass smoke from wildland fires raging near Lake Baikal in south-central Russia (7 Aug 2015); and (d) desert dust pooling over central China (27 Apr 2015). Animations of these cases for uncorrected, SHCS, and HAC true-color imagery are available at [http://dx.doi.org/10.1175/BAMS-D-15-00154.2](http://dx.doi.org/10.1175/BAMS-D-15-00154.2).
(shortwave water vapor) band, and in the case of GOES-R that came at the expense of the green band. Ultimately, true-color imagery lacked a “validated user requirement” (Schmit et al. 2003) strong enough to outrank higher priority requirements. Adding weight to the true-color requirement in the future will take a formal assessment by the international user community, demonstrating how the information content of true-color imagery is of practical value for scene interpretation (including delineation of visibility hazards such as smoke and blowing dust). Quantitative metrics, such as determining an analyst’s ability to distinguish smoke, dust, and cloud features using true-color versus standard VIS–NIR–IR imagery in a time-limited setting, or development of objective color-space feature discrimination algorithms, would be useful in this regard. Despite the specific limitations of this new generation of GEO sensors for rendering true-color imagery, it is important to remember that their overall abilities represent a tremendous advance, and we have demonstrated here that via simple techniques the obstacles are at least partially surmountable.

An important lesson learned for the design of future sensors intended for true-color imaging is to center their green band’s peak sensitivity, near 0.55 µm. The Coordination Group for Meteorological Satellites (CGMS) is perhaps the most appropriate purveyor of this best-practices guidance to the international community of meteorological satellite developers. In the meantime, and in the immediacy of next-generation GEO systems coming online, it is likely that the international user community will instead adopt some version of this effective and straightforward hybrid green technique to mitigate the 0.51-µm deficiencies when producing true-color imagery for their respective programs.

The situation is a bit more complicated for the U.S. program, but remains manageable. The ABI, which will fly on NOAA’s next-generation GOES-R series and was in fact built by the same vendor as AHI, carries 16 spectral bands as well. However, ABI will include a NIR band centered at 1.38 µm instead of a green band. The 1.38-µm band, not present on AHI, holds great value in its own right, being able to detect daytime cirrus (Gao et al. 2002) owing to its unique spectral location in the center of a strong water vapor absorption band. However, it leaves GOES-R without an immediate means for rendering true-color imagery from its native suite of bands.

In this regard, the current AHI research takes on added significance—preparing the way for advanced techniques that will enlist Himawari-8 AHI as training for a “synthetic” or “virtual” green band, via correlations that exist between green and adjacent VIS/NIR bands (e.g., Miller et al. 2012; Hillger et al. 2011; Gladkova et al. 2011). Since AHI contains blue, red, and vegetation bands common to ABI, along with the requisite green band, it can be used as the superset of spectral information necessary to formulate this relationship. These ABI-preparatory developments represent the next logical pursuits of the current research.

**CONCLUSIONS.** At long last, Japan’s Himawari-8 AHI marks the return of true-color capabilities to the geostationary platform. While first-light imagery revealed a suboptimal green band, through a bit of “spectral smithery,” a hybrid technique has been crafted to overcome this band’s main deficiencies. A subtle blend of the native 0.51-µm green band with the 0.86-µm vegetation band produces a selectively boosted green band yielding true-color imagery that is consistent with the appearance of legacy polar-orbiting sensors. The HAC correction is by no means a panacea, but in the realm of multispectral imagery enhancement development (which often resorts to a kind of “whack-a-mole” game, wherein the fixing of one issue gives rise to yet another issue, with iterations continuing ad infinitum), the availability of a simple, bispectral solution is serendipitous. It can be regarded as a positive outcome to what might otherwise have meant going without high-quality true-color imagery on the GEO platform.

It is worth noting that NASA’s Earth Polychromatic Imaging Camera (EPIC) on the Deep Space Climate Observatory (DSCOVR; Early et al. 2002), launched on 11 February 2015, now provides a unique true-color imagery capability from the Lagrange-1 orbit (L1; 1.6 million km away from Earth at a gravitationally stable point between Earth and the sun) that views the daylit side of Earth on a nearly continual basis. Since L1 is not by definition a GEO orbit, there is only one view from a given longitudinal perspective per day, provided at roughly 10-km (subsatellite point) resolution, hourly data, and at 12-h latency. This is an important distinction between the two platforms; the GEO imagers provide 10–15-min full-disk updates at 10 min latency, with approximately 1-km resolution at subpoint and a fixed viewing perspective. The unique perspective of EPIC holds value for numerous quantitative applications in terms of multangle viewing (e.g., for cloud/aerosol geometric and optical properties). While the EPIC data are not a viable alternative to scene-fixed, high-space–time-resolution GEO observations, they offer a novel way of viewing Earth...
and a gap filler to true-color imaging from the nascent GEO constellation.

After going without a true-color capability on GEO satellites for nearly 50 years, we suddenly find ourselves in an embarrassment of riches, with true-color-equipped sensors on the LEO, GEO, and L1 orbits. True color plays a far greater role than simply serving as the flagship public relations material for our next-generation GEO programs; it offers the human analyst a practical tool for intuitive scene interpretation. Over the next decade, the full international complement of GEO sensors will begin using true color to reveal the dynamic Earth–atmosphere system in an entirely new, yet inherently familiar way. While it may require some fine tuning and processing “HACs” for the time being, true-color imagery is back on GEO, and hopefully this time it is here to stay!

ACKNOWLEDGMENTS. Support of the NOAA GOES-R Program Office, the Naval Research Laboratory (Contract N00173-14-G902), the Oceanographer of the Navy PEO C4I and Space/PMW-120, Program Element PE-0603207N, and the Office of Naval Research (Contract N00014-16-1-2040) are gratefully acknowledged. The authors and should not be construed as an official NOAA and/or U.S. Government position, policy, or decision. We thank Jean Phillips and Jaclyn Lang of the SSEC Schwertdfeger Library for providing background material on ATS-3. More information on true-color images can be found with the following search keywords: JMA AHI imagery, CIRA true-color AHI, SSEC geostationary browser AHI, and SSEC Real Earth AHI true color. Real-time AHI imagery can be found at http://rammb.cira.colostate.edu/ramsdis-online/himawari-8.asp. Various blog entries expanding on the capabilities of Himawari-8 can be found at http://cimss.ssec.wisc.edu/goes/blog/archives/category/himawari-8. Finally, a web-based application intended to help users better understand RGB formulation, including the effects of atmospheric correction, can be found at http://cimss.ssec.wisc.edu/goes/webapps/satrgb/satrgb_AHI_color.html.

REFERENCES


Purdom, J. F. W., 1976: Some uses of high-resolution GOES imagery in the mesoscale forecasting of


A statistical framework for evaluating definitions of extreme weather phenomena can help weather agencies and health departments identify the definition(s) most applicable for alerts and other preparedness operations related to extreme weather episodes.

**A STATISTICAL FRAMEWORK TO EVALUATE EXTREME WEATHER DEFINITIONS FROM A HEALTH PERSPECTIVE**

**A Demonstration Based on Extreme Heat Events**

*by Ambarish Vaidyanathan, Scott R. Kegler, Shubhaya S. Saha, and James A. Mulholland*

An extreme heat event (EHE) is defined as a sustained period of abnormally and uncomfortably hot, and usually humid, weather (Meehl and Tebaldi 2004). EHEs can negatively impact vital aspects of society, including agriculture, power production and consumption, and human health (National Research Council 2010; IPCC 2007). In the United States, fatalities related to naturally occurring ambient temperature extremes (hypothermia or hyperthermia) account for far more deaths in most years than those resulting from the combined effects of natural disasters such as storms and floods (Berko et al. 2014). The relationship between extreme temperature and mortality has been well described (Barnett et al. 2012; Barnett et al. 2010; Curriero et al. 2002; Medina-Ramon and Schwartz 2007), and studies have reported an added effect of heat waves independent of the effects of individual daily temperature extremes (Anderson and Bell 2011; Gasparrini and Armstrong 2011; Hajat et al. 2010; Hertel et al. 2009). Previous studies have also explored the sensitivity of the temperature–mortality relationship to different measures of temperature, as well as the duration and threshold type/intensity, used to define EHEs (Barnett et al. 2012; Barnett et al. 2010). Adverse health outcomes associated with EHEs are often preventable (Fowler et al. 2013; Choudhary and Vaidyanathan 2014); however, it is imperative to identify such events in advance and take measures to reduce the public health risk.

Many EHE definitions are available from the literature (Anderson and Bell 2011; Basagaña et al. 2015; CDC 2013; Easterling et al. 2000; Hajat et al. 2006; Hajat et al. 2010; Huth et al. 2000; Kent et al. 2014; Kovats and Hajat 2008; Meehl and Tebaldi 2004; Nairn and Fawcett 2014; Pascal et al. 2006; Pascal et al. 2013; Peng et al. 2011; Robinson 2001; Smith et al. 2013). Typical EHE definitions can be decomposed into the following core variables:

1) daily heat metric—heat metrics, such as daily maximum and mean temperature, and diurnal temperature difference are typically employed in EHE definitions;
2) duration—the number of consecutive days of extreme heat needed to constitute an EHE; the minimum duration for most definitions varies from 2 to 4 days;

3) threshold type—absolute, which is based on a daily heat metric threshold that does not change, or relative, which is based on an exceedance above a set percentile, which varies according to the underlying daily heat metric distribution for a given location; and

4) threshold intensity, which indicates the extremity of deviation considered to represent exposure to extreme heat. Most definitions refer to exceedances above absolute thresholds such as 90°, 95°, 100°, or 105°F or exceedances above relative thresholds such as 95th, 97th, 98th, or 99th percentiles.

Extreme heat exposures (distinct from EHEs) have been defined using thermal indices, which are derived based on human energy balance and incorporate physiological attributes as well as the effects of the thermal environment on human health (Cheng et al. 2012; Höppe 1999; Matzarakis et al. 1999; Nastos and Matzarakis 2012; Parsons 2014; Vanos et al. 2012). Additionally, EHEs have been defined using biometeorological indices that utilize ambient temperature and other relevant weather parameters; widely used examples of such indices are wet-bulb globe temperature (Budd 2008), apparent temperature (heat index) (Rothfusz 1990), humi-index (Vaneckova et al. 2011), the Thom discomfort index (Thom 1959), and the spatial synoptic classification (SSC) (Sheridan et al. 2009). Of note is that the SSC is an airmass-based categorical classification system that is customized to a geographic area using retrospective health data and has been adopted by some local weather forecast offices in the United States (Hondula et al. 2014).

Within the context of the outline above, EHEs are defined using several daily heat metrics but are primarily based on meteorological variable deviations (e.g., temperature) from the historical norm, and a majority of studies have applied one definition to all climate regions. Studies that have evaluated EHEs are limited to a few geographic areas (Gasparrini and Armstrong 2011; Hajat et al. 2010; Ishigami et al. 2008) and extending definitions from such studies to the entire United States could result in the misidentification of EHEs in terms of human health effects. Some studies that have been published evaluated EHE definitions using health data (Anderson and Bell 2009; Hajat et al. 2010; Kent et al. 2014; Pascal et al. 2006; Zhang et al. 2012) but almost all of the studies conducted nationally failed to evaluate EHE definitions using data on health outcomes having a clear causal link to extreme heat. On the whole, there is a lack of consensus in the scientific literature on definitions and procedures to accurately identify...
periods of extreme heat having the potential for adverse health impacts.

Issuance of alerts and health advisories, prior to or during extreme weather events, can be critical to averting adverse health outcomes and is a service currently supported by weather and public health agencies involved in preparedness, response, and recovery operations. Alerts and health advisories are presumably most effective when based on weather event definitions that best reflect related health concerns. In this paper, we use episodes of extreme heat as an example to illustrate the application of a statistical framework within which to evaluate a candidate set of definitions in the context of heat mortality.

The evaluation is conducted by climate regions, recognizing that populations living under different prevailing climate conditions might adapt differently to weather-related exposures, including episodes of extreme heat (Davis et al. 2003), which in turn allows for the possibility that the most appropriate definitions might vary with climate region. Although we demonstrate the application of this framework to identify appropriate EHE definitions using county-level heat mortality data, the basic framework might also be applied to data describing other extreme weather events with well-established links to adverse health outcomes and, potentially, at other levels of geography.

**METHODS.** *Meteorological data.* We used station-based meteorological data for the years 1999–2009, and any county in the contiguous United States (lower 48 states) that had an automated surface observing system (ASOS) unit (NOAA/NWS 1999) was considered for the present demonstration. We obtained these data from the National Oceanic and Atmospheric Administration’s National Centers for Environmental Information (NCEI; www.ncei.noaa.gov). The spatial coverage of the ASOS stations is shown in Fig. 1. For each station we adopted a completeness criterion requiring nonmissing values for at least 75% of the hourly weather observations in a given day (at least 18 of 24 hourly measurements) for purposes of calculating daily heat metric summaries. For each county and day, a county-level estimate was calculated as the average of all available station-level heat metric summaries. Counties with estimates for at least 95% of the days covered by the summer months (1 May–30 September) of each individual year (1999–2009) were included in the demonstration dataset.

**EHE definitions and core variables.** For this study, we considered a number of EHE definitions that have been used in public health research and/or widely cited in the literature. Table 1 summarizes the different combinations of core variables used to define an EHE in this analysis. We used daily maximum temperature ($T_{\text{max}}$), daily maximum heat index ($HI_{\text{max}}$), daily average temperature ($T_{\text{avg}}$), and a combination of $T_{\text{max}}$ and daily minimum temperature ($T_{\text{min}}$) as daily heat metrics; all heat metrics were represented in degrees Fahrenheit and we used the formula cited in Robinson (2001) to compute $HI_{\text{max}}$.

We considered EHE definitions with both absolute and relative thresholds. Absolute thresholds were set at various intensity values, including 90°F, 95°F, 100°F, and 105°F. Relative thresholds were calculated using two different approaches. We calculated percentile-based relative thresholds representing different intensities, including the 80th, 85th, 90th, 95th, 98th, and 99th percentile values and, for one definition, that of Huth et al. (2000).1 We used the 81st and 97.5th percentile values. We computed these percentiles using heat metric data for the summer months for the years 1999–2009. We obtained station-level climate normal information from the NCEI, that is, the mean and standard deviation of the daily heat metrics computed based on data from 1981 to 2010 (Arguez et al. 2012); climate normals were unavailable for the heat index. We operationalized EHE definitions with minimum duration, that is, the number of consecutive days needed to constitute an EHE, variously ranging from 2 to 4 days. Varying minimum durations coupled with the various thresholds for each daily heat metric resulted in a total of 92 variants (Table 1). Table ES1 (in the online supplemental material; http://dx.doi.org/10.1175/BAMS-D-15-00181.2) provides precise details for each of these variants. We operationalized each EHE definition/variant using a binary [yes (1) or no (0)] variable, classifying each day in each county during the summer months as either an “EHE day” or a “non-EHE day.”2 Days for which daily county-level data were not available could in some instances have interrupted a data sequence that might otherwise

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1 Per Huth’s definition, a heat wave is defined as the longest period of consecutive days satisfying the following three conditions: 1) the daily maximum temperature is above $T_1$ (97.5th percentile) for at least three consecutive days, 2) the daily maximum temperature is above $T_2$ (81th percentile) during the entire period, and 3) the average of the daily maximum temperature over the entire period is greater than $T_1$.

2 We added a buffer of 3 days to the start and end of the summer months to account for any potential EHE that either started prior to 1 May and ended on or shortly after 1 May, or started on or shortly before 30 September and ended in the early part of October. The buffer days were not included in the analysis.
TABLE I. Core variables used in EHE definitions. Capital X’s indicate definitions used in this analysis; boldface X’s with asterisks indicate definitions published in the literature.

<table>
<thead>
<tr>
<th>Daily heat metric</th>
<th>Duration (days)</th>
<th>Relative threshold</th>
<th>Climate-normal-based threshold</th>
<th>Absolute threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P80</td>
<td>P85</td>
<td>P90</td>
<td>P95</td>
</tr>
<tr>
<td>Daily max temp (T_{max})</td>
<td>≥2</td>
<td><em>X</em></td>
<td><em>X</em></td>
<td><em>X</em></td>
</tr>
<tr>
<td></td>
<td>≥3</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>≥4</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Daily avg temp (T_{avg})</td>
<td>≥2</td>
<td><em>X</em></td>
<td><em>X</em></td>
<td><em>X</em></td>
</tr>
<tr>
<td></td>
<td>≥3</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>≥4</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Daily max heat index (HI_{max})</td>
<td>≥2</td>
<td><em>X</em></td>
<td><em>X</em></td>
<td><em>X</em></td>
</tr>
<tr>
<td></td>
<td>≥3</td>
<td><em>X</em></td>
<td><em>X</em></td>
<td><em>X</em></td>
</tr>
<tr>
<td></td>
<td>≥4</td>
<td><em>X</em></td>
<td><em>X</em></td>
<td><em>X</em></td>
</tr>
<tr>
<td>Daily max and min temp (T_{max} and T_{min})</td>
<td>≥3</td>
<td><em>X</em></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Huth\(^a\) ≥3 *X*

\(^a\) Per Huth’s definition, a heat wave is defined as the longest period of consecutive days satisfying the following three conditions: 1) the daily maximum temperature is above T1 (97.5th percentile) for at least three consecutive days; 2) the daily maximum temperature is above T2 (81th percentile) during the entire period; and 3) the average of daily maximum temperature over the entire period is greater than T1.

...
such data) and made adjustments to account for county boundary changes that occurred between 1999 and 2009 (www.census.gov/geo/reference/county-changes.html).

Population and other ancillary data. For incidence rate denominators we used county-level bridged-race population estimates developed by NCHS and the U.S. Census Bureau (www.cdc.gov/nchs/nvss/bridged_race.htm). In addition to the meteorological data described in the meteorological data section above, we note the availability of a number of county-level measures of health, behavior, and economic conditions that could influence heat-related health outcomes. Percentages of residents of all ages living in poverty and percentages of residents aged 0–64 years without health insurance are available from the U.S. Census Bureau; prevalence estimates of current adult smokers are available from the Centers for Disease Control and Prevention (CDC) Behavioral and Risk Factor Surveillance System; data on diabetes prevalence, adults that reported no leisure-time physical activity, and obesity prevalence (body mass index ≥ 30) are available from the CDC National Center for Chronic Disease Prevention and Health Promotion, Division of Diabetes Translation, while residential air conditioning prevalence data are available from a private vendor (efficiency 2.0). For the present demonstration, however, we felt that these data could not be meaningfully summarized across entire climate regions, as would be necessary for their inclusion in the modeling process described subsequently (see the section on rate regression modeling below). While EHEs tend to occur over broad geographic scales (and can thus be plausibly summarized across regions), measures such as those identified above might be expected to vary at more localized scales.

Evaluating EHE definitions using heat mortality data. Separately evaluating 92 different EHE definitions/variants and compiling results could become unmanageable from an operational standpoint; hence, we used cluster analysis as a preliminary data reduction technique to group EHE definitions into homogeneous sets. We differentiated any two EHE definitions based on county-day disagreements between the binary variables representing the operationalized definitions. For a given county and year, the total count of daily disagreements between two definitions is provided by the sum of the off-diagonal frequencies, as shown in Table ES2 in the online supplemental material to this article. (This sum represents the squared Euclidean distance between two vectors of binary variables.) Because the main research focus is on human health effects, these counts were weighted by the yearly county population estimates in order to ensure proportional representation. The population-weighted disagreement counts were then summed across counties (nationwide) and years to obtain an overall measure of disagreement (or distance) between the two EHE definitions. A distance matrix containing the overall disagreement measures for all pairs of EHE definitions (4,186 pairs) was used as input into the clustering procedure.

We applied a hierarchical clustering technique and employed an average distance metric to determine distances between clusters that might be merged in each step of the clustering process (Kalkstein et al. 1987; Zhang et al. 1996). Average distance is calculated using the formula

$$d(C_a, C_b) = \frac{\sum_{i=1}^{n_a} \sum_{j=1}^{n_b} d(a_i, b_j)}{n_a \times n_b},$$

where $C_a$ and $C_b$ are two disjoint clusters; $n_a$ and $n_b$ are the number of members within clusters $C_a$ and $C_b$, respectively; and $d$ is the squared Euclidean distance between two members of the two disjoint clusters.

We divided the final hierarchical cluster (one large cluster encompassing all definitions) into smaller clusters, taking into consideration various diagnostics including the $R$-squared, pseudo-$F$, and pseudo-$t$-squared indices. Based on these diagnostics, we identified relatively distinct high-level clusters. One representative EHE definition was then selected from each high-level cluster. Representative definitions were selected according to the following criteria: 1) EHE definitions/variants that are well recognized in the literature, 2) application in studies conducted in the United States, and 3) application in nationally representative studies (i.e., those studies that covered the various climate regions of the United States). Recognizing the possibility of delayed or extended health effects associated with EHEs, each representative EHE definition was combined with the following exposure offsets: no lag (i.e., no offset), a 1-day lag, and 1-, 2-, and 3-day extended (post-EHE) effects (Fig. 2).

Rate regression modeling. We applied rate regression models to evaluate the relationship between operationalized EHE definitions and heat deaths. The following model was used to estimate the death rate per person day for each EHE definition/variant and exposure offset combination:
log(E[D]/P) = α + β_{region} + β_{EHE} × EHE
+ β_{EHE.Region} × EHE × Region, \quad (2)

with model terms defined as follows: \( D \) is the count of deaths for each combination of region, year, and EHE status; \( E[D] \) is the expected count of deaths; \( P \) is the number of person-days of exposure for which \( D \) is measured; \( α \) is the intercept; \( β_{region} \) is the intercept offset for the climate region; \( β_{EHE} \) is the effect parameter for the binary variable representing the operationalized EHE definition/variant and exposure offset combination; EHE is the binary variable representing the operationalized EHE definition/variant and exposure offset combination; \( β_{EHE.Region} \) is the effect parameter for the interaction between the region and EHE; and Region is the classification (indicator) variable for the region.

To compensate for overdispersion, we specified a negative binomial link. Using this modeling approach, we estimated region-specific baseline rates of the heat death (in the absence of an EHE) and region-specific EHE rates of heat death (in the presence of an EHE). We termed the estimated increases in rates due to EHEs as “EHE effects.”

We used the estimated EHE effects to identify the “best” EHE definition/variant and exposure offset combinations for each region. One might hypothesize that there is some “gold standard” EHE definition that best explains heat mortality; the various EHE definitions considered in this evaluation represent approximations to this hypothetical gold standard. The extent to which each operationalized EHE definition deviates from the hypothetical gold standard can be expected to materialize in the form of attenuation bias (i.e., weaker estimated EHE effects than might be ideally attained). By this reasoning, the strongest estimates, presumably corresponding to those with the least attenuation bias, are assumed to best represent the gold standard. We tested this reasoning by simulating various “ideal” datasets, each with health outcomes following a probability distribution conforming to a different (and arbitrary) gold standard EHE definition, and then observing the influence of deviations from the gold standard. The steps in our simulation exercise are described in Fig. 3.

After the simulation exercise indicated that the attenuation bias concept is applicable to our situation, we employed model (2) to identify the EHE definition/variant and exposure offset combinations having the strongest effect estimates. We evaluated each of the EHE definitions/variants selected as high-level cluster representatives crossed with the five exposure offsets and ranked the results in descending order based on the lower confidence limit associated with each EHE effect estimate, for each climate region. Further, to characterize the region-specific differences in population-level susceptibility to extreme heat, we conducted a random effects meta-analysis, by region, based on the 10 “best” region-specific EHE definition/variant and exposure offset combinations, to estimate the mean baseline rate, the mean EHE effect, and associated confidence intervals (CIs) for each region. We carried out our data analyses using the Statistical Analysis System (SAS version 9.3), Environmental Systems Research Institute’s GIS software (ESRI, ArcGIS version 9.3), and comprehensive meta-analysis software (CMA version 2.0).

**RESULTS.** Table 2 summarizes the number of heat deaths and counties with meteorological data, by climate region. A total of 3,829 heat deaths were identified for the contiguous United States during the summer months of 1999–2009, and 2,218 (58%) of these deaths were among residents of counties with meteorological data meeting the stated completeness criterion (complete data). For the latter group the state of residence and the state where death occurred were the same in 94% of cases; the county of residence and the county where death occurred were the same in 83% of cases and in another 6% of cases the counties were geographically adjacent. The average fraction of the U.S. population living in counties with complete meteorological data was 57% over the 11-yr period considered here. The South region had the largest number of counties with complete meteorological data (\( n = 91 \)) and also the largest number of heat deaths (\( n = 481 \)) among residents of those counties. The West region had the smallest number of counties (\( n = 38 \)) with complete meteorological data, although counties in this region are notably among the most geographically expansive. The North West Central region, which was formed by combining the Northwest and West North Central regions, had the smallest number of heat deaths (\( n = 72 \)) among residents of counties with complete meteorological data.

Figure 4 shows a dendrogram (or cluster tree), which depicts the sequential clustering of the EHE definitions/variants in a hierarchical manner. We delineated the final high-level clusters, taking into consideration the \( R \)-squared, pseudo-\( R \), and pseudo-\( t \)-squared indices (data not shown). The break points were also influenced.
by subjective assessments of the homogeneity of members within clusters and the heterogeneity across clusters. We ultimately settled on five high-level clusters. We labeled each high-level cluster to reflect the underlying feature(s) common to the definitions/variants comprising it. Cluster 1 was the first cluster delineated and it contains only definitions/variants that are based on absolute thresholds for several of the daily heat metrics. Cluster 2 contains definitions/variants based on thresholds that are predominantly moderate in intensity. Cluster 3 contains definitions/variants based on thresholds that are slightly more severe than those for cluster 2. Cluster 4 contains definitions/variants based on thresholds that are predominantly extreme in nature. Cluster 5 consists of definitions/variants that rely on relative thresholds constructed from long-term climate-normal data, with thresholds that are predominantly low. Table ES3 in the online supplemental material lists the EHE definition/variant that was selected as the representative from each high-level cluster. The five representative EHE definitions/variants crossed with the five exposure offsets resulted in 25 different combinations to be evaluated using the rate regression modeling framework.

Table 3 ranks the EHE definition/variant and exposure offset combinations by climate region. The representative definition/variant from cluster 3, daily maximum temperature greater than the 95th percentile for at least two consecutive days, is most strongly associated with heat mortality for six of the eight climate regions. The combinations of this definition/variant with exposure offsets representing a 1-day lag (Lag1) or no lag (Lag0) show the strongest estimated EHE effects for all regions except the Southwest and South. The representative definition/variant from cluster 1, daily maximum heat index greater than 90°F for three consecutive days, combined with each of the different exposure offsets, shows the strongest estimated EHE effects for the Southwest. The representative definition/variant from cluster 4, the Huth definition, was the best definition for the South but generally shows the weakest estimated EHE effects for other regions. The representative definition/variant from cluster 2, daily maximum and minimum temperature greater than the 80th percentile for at least three consecutive days, ranked fairly high (depending on the exposure offset) for the Central, Northeast, and

**Fig. 2. Exposure offsets.**

**Fig. 3. Simulation exercise to test the attenuation bias concept.**
Southeast regions; Lag1 and Lag0 represent the best exposure offsets. The representative definition/variant from cluster 5, daily mean temperature greater than the mean plus one standard deviation of the long-term climate normal for at least three consecutive days, shows the weakest estimated EHE effects overall. For most regions, no one definition/variant is distinctly superior to all others. We also provide a table in the online supplement (see Table ES4) that describes other metrics such as the percentage of days classified as EHE days and percentage of heat deaths covered by EHE days for each representative EHE definition/variant and exposure offset combination.

Table 4 provides the results of the random effects meta-analyses of the estimated baseline rates and EHE effects, based on the 10 best EHE definition/variant and exposure offset combinations, for each climate region. The North West Central region shows the lowest mean (95% CI) baseline rate, 1.8 (1.5–2.2) deaths per one billion person-days of risk, and the highest mean (95% CI) EHE effect of 22.0 (17.7–27.3). The South region shows the highest mean (95% CI) baseline rate of 10.0 (8.8–12.0) deaths per one billion person-days of risk. The lowest mean EHE effect of 6.2 (4.9–7.9) was observed in the Southeast. In general, colder regions of the United States show a relatively low baseline rate and a relatively high EHE effect, while the warmer regions of the United States show a relatively high baseline rate and a relatively low EHE effect.

**SUMMARY AND PERSPECTIVES.** EHE definitions used for issuing alerts in most heat warning systems are calibrated to the extreme end of the daily heat metric spectrum. As noted by Hajat et al. (2010), our findings similarly suggest that using a definition that only identifies extremely hot days may have a greater tendency to introduce false negatives and thereby underestimate the risks associated with extreme heat, whereas using a less stringent threshold for EHE definitions may have a greater tendency to introduce false positives and thereby overestimate the risks. Additionally, prior approaches to evaluating EHE definitions that relied on mortality data mostly considered deaths due to all causes (Gasparrini and Armstrong 2011; Hajat et al. 2010; Zhang et al. 2012). The relationship between all-cause mortality and extreme heat is confounded by other factors, including long-term trends in mortality and various sociodemographic factors (Anderson and Bell 2009; Reid et al. 2009; Semenza et al. 1996). While this may also be true of the relationship between heat-related health outcomes and extreme heat, the extent of confounding might be expected to be less pronounced because of the presumably stronger causal link between the exposure and such outcomes.

To the best of our knowledge, the framework described here represents the first nationally consistent scheme for evaluating definitions of extreme weather events, within the context of adverse health outcomes with clear causal links to exposures characterized by such definitions. The framework, applied here to the evaluation of EHE definitions, employs cluster analysis to identify homogeneous groupings of event definitions followed by rate regression modeling to estimate the effects for representatives from these groupings. It provides a cohesive approach to identifying those definitions (and their variants) most closely associated with the adverse health outcome(s) of interest. Moreover, the approach can also shed light on definitions that are
most weakly associated with adverse health outcomes. For example, in our demonstration, EHE definitions with thresholds that are either too extreme or too moderate tend to be among those most weakly associated with heat mortality for most climate regions.

Extending the basic framework to include a random effects meta-analysis proved useful in summarizing baseline health risks and event-specific effects for different climate regions. As exemplified in this demonstration, the warmer regions of the United States experience higher mortality rates compared to the cooler regions.
## Table 3. Rankings of representative EHE definition and exposure offset combinations derived using the statistical framework, by U.S. climate region. The table values highlighted in bold are the top 5 EHE definition and exposure offset combinations for that region.

<table>
<thead>
<tr>
<th>EHE definition</th>
<th>ExE1</th>
<th>ExE2</th>
<th>ExE3</th>
<th>Lag0</th>
<th>Lag1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily max heat index greater than 90°F for at least 3 consecutive days</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td>EHE effect (95% CI)</td>
</tr>
<tr>
<td>Daily max temp greater than the 80th percentile for at least 3 consecutive days</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td>EHE effect (95% CI)</td>
</tr>
<tr>
<td>South</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td>EHE effect (95% CI)</td>
</tr>
<tr>
<td>Southwest</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td>EHE effect (95% CI)</td>
<td>Rank</td>
<td></td>
</tr>
</tbody>
</table>

**Central**

- **Daily max heat index greater than 90°F for at least 3 consecutive days**

  - ExE1: 13.1 (8.4, 20.4)
  - ExE2: 12.6 (8.1, 19.7)
  - ExE3: 12.1 (7.7, 19.1)

- **Daily max temp greater than the 80th percentile for at least 3 consecutive days**

  - ExE1: 14.8 (9.3, 23.5)
  - ExE2: 14.5 (9.2, 23.0)
  - ExE3: 13.8 (8.7, 21.8)

**Northeast**

- **Daily max heat index greater than 90°F for at least 3 consecutive days**

  - ExE3: 22.0 (13.7, 35.3)

- **Daily max temp greater than the 80th percentile for at least 3 consecutive days**

  - ExE2: 12.5 (7.0, 22.4)

**Southeast**

- **Daily max heat index greater than 90°F for at least 3 consecutive days**

  - ExE3: 15.2 (9.6, 24.0)

- **Daily max temp greater than the 80th percentile for at least 3 consecutive days**

  - ExE3: 13.1 (8.3, 20.7)

**South**

- **Daily max heat index greater than 90°F for at least 3 consecutive days**

  - ExE3: 15.6 (8.8, 27.7)

- **Daily max temp greater than the 80th percentile for at least 3 consecutive days**

  - ExE3: 15.3 (8.5, 27.4)
States appear to have relatively modest EHE effects coinciding with relatively high baseline rates, whereas colder areas of the United States have relatively strong EHE effects coinciding with low baseline rates. This may indicate that in warmer regions, some summer days that are not classified as EHE days are nonetheless warm enough to put susceptible populations at an elevated risk for adverse heat-related health outcomes. To the extent that this might elevate estimated baseline rates, it would simultaneously offset estimated EHE effects. Prior knowledge of such geographic differences in health risks over an event timeline (prevent, event, and postevent) could potentially assist public health practitioners and emergency planners with advance preparations for extreme weather events.

While our demonstration relied on heat mortality data to evaluate EHE definitions, the general framework might be applied to other adverse health outcomes with well-established links to extreme weather events. Further, considering a fuller range of outcome severity, including nonfatal hospitalizations and emergency department visits, might allow application of the framework at finer levels of geography such as cities and/or greater metropolitan areas. Applying the framework at finer geographic scales could facilitate the integration of measures reflecting local population attributes into the modeling process, as potential confounders or modifiers of the relationship between extreme weather and related health outcomes. For example, air conditioning (a material adaptation) is a significant protective factor for heat-related health outcomes (Reid et al. 2009). Studies have also shown differing degrees of susceptibility to extreme heat among different ethnic groups (Klinenberg 2002; Klinenberg 2003). 

Incorporating such factors into the evaluation scheme might also provide information useful for community-specific response plans.

There are some limitations to the present demonstration. Because we used station-based measurements as the source of the ambient heat data, approximately 40% of heat deaths nationwide were excluded. While sparseness in the region-wide numbers of heat deaths did not lead to convergence or statistical power issues in the modeling process, it prevented us from conducting an evaluation at a finer geographic scale. However, our ultimate goal was not to evaluate different EHE definitions but rather to present a general statistical framework for ranking EHE definitions, independent of geographic resolution to the extent

Fig. 5. Potential uses of the statistical framework.
possible. Relying on ambient weather data may also misrepresent true individual-level exposures, particularly in regions where summertime indoor climate control is widely employed (Davis et al. 2003) and in places where weather stations are not in close proximity to population centers. Further, this study did not consider daily heat metrics that are calculated using sophisticated algorithms and/or involve several synoptic weather parameters to identify EHEs; however, in this regard at least one other study noted a high degree of agreement among different temperature metrics used to characterize EHEs (Barnett et al. 2010). Finally, the mortality data used to test our framework are based on death certificates, which in some instances could lead to misclassification of deaths resulting from extreme heat exposure (Combs et al. 1999).

CONCLUSIONS. Increasingly, collaborations between public health and weather agencies are growing into a community of practice with an interest in examining the impacts of a wide range of extreme weather events on human health and the accompanying economic burdens. The evaluation framework proposed here, based on systematic but flexible statistical components, could be adopted by this community of practice to validate existing (or newly proposed) definitions of extreme weather events used to issue alerts and mitigate adverse health impacts. The schematic presented in Fig. 5 illustrates how the proposed framework might be adopted by agencies involved in emergency preparedness and response operations and identifies potential end-user benefits resulting from identifying definitions that are most appropriate from a health perspective. For example, once the definitions for extreme heat most directly associated with heat-related health outcomes have been identified, statistical modeling approaches could be extended to quantify all excess deaths and illnesses associated with EHEs over historical (decadal) time scales, provided the necessary meteorological and health data are available. Noting that climate change is projected to increase the frequency and/or magnitude of EHEs (Morss et al. 2011), estimates of the historical (and projected) health burden associated with EHEs might help identify vulnerable populations and also inform adaptation efforts.

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REFERENCES


This article discusses the evolution of CoCoRaHS, the nationwide citizen science network of precipitation observers, during the past 10 years.
The Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) is a precipitation monitoring network composed of thousands of volunteers manually measuring precipitation in a consistent way and reporting data online (www.cocorahs.org). The network, which began as a local community project in response to a local flash flood (Kelsch 1998), has expanded over time to provide informal weather and climate education opportunities for the public, and it has evolved to provide high-quality daily precipitation data that are used and depended upon by numerous entities throughout the country. CoCoRaHS was first described in the Bulletin of the American Meteorology Society (BAMS) 10 years ago (Cifelli et al. 2005). What was at that time a small five-state network of volunteer observers has grown into a nationwide leading citizen science example with approximately 20,000 active participants (many reporting every day), throughout the United States, Puerto Rico, the U.S. Virgin Islands, and 13 Canadian provinces. CoCoRaHS is now the largest provider of daily manual rainfall measurements in the United States and is one of the larger citizen science networks in the world (Fig. 1). 

In March 2015 the federal government even became part of the program with a gauge located in the First Lady’s vegetable garden at the White House (station DC-DC-19). A total of 37,500 observers have made observations as part of the network during its 17-yr history with over 31 million daily reports recorded and archived. Assuming conservatively that each daily observation takes about three minutes to measure and report online, this represents a volunteer contribution on the order of 1.5 million hours. In addition, there have been tens of thousands of supplemental reports of hail, heavy rain, snow, and drought conditions.

This article looks at the evolution and accomplishments of this maturing network.

NATIONAL EXPANSION: 2005–09. The landscape of CoCoRaHS was very different 10 years ago. A staff of two and a handful of volunteer leaders oversaw the development of a network of rain gauge volunteers in Colorado, Wyoming, and Kansas. At the same time, Nebraska followed the Colorado model by establishing its own network—the Nebraska Rainfall Assessment and Information Network (NeRAIN) (http://nerain.dnr.ne.gov/nerain/), Texas and New Mexico were just joining the network then. Thanks to National Science Foundation funding, CoCoRaHS became more visible to the scientific community though participation in several national conferences. Scientists and educators were just beginning to hear of the oddly named organization—CoCoRaHS (pronounced KO-ko-rozz)—that most could neither spell nor pronounce.

With the hiring of a full-time national coordinator late in 2004, the vision for CoCoRaHS shifted from local and regional to national. A nationwide network could potentially fill gaps where precipitation was not being measured by “official” networks, and it could possibly be done with a volunteer force of interested citizens who would learn about their climate while doing something useful for their community. The National Weather Service (NWS) also played a significant role. One of its forecasters from the Boulder (Colorado) NWS Forecast Office wrote some computer code that effectively made CoCoRaHS real-time reports of heavy rain, freezing rain, heavy snow, and/or hail immediately available as an alert message to the appropriate forecast office anywhere in the country. This provided NWS offices immediate motivation to participate in CoCoRaHS and to encourage its expansion. And so the national expansion began (CoCoRaHS 2013). Methodically, on a state-by-state basis CoCoRaHS grew. An Environmental Literacy grant from the National Oceanic and Atmospheric Administration (NOAA)’s Office of Education in 2006 gave the network funding and further motivation to enlarge its footprint across the country. Through partnerships with the National Weather Service and state climatologist offices (both of which needed, appreciated, and had the immediate capacity to use more and better precipitation data from widespread locations in each state), teams of volunteer state leaders were developed. Recruiting and publicity strategies were developed, press releases were issued, and the recruitment of observers intensified. States such as North Carolina and Kentucky launched large CoCoRaHS kickoff campaigns (ASU 2007; http://wwwagwx.ca.uky.edu/cocorahs.mp3). With the addition of Minnesota in December of 2009, all 50 states were part of the network. Along the way several
smaller existing precipitation networks in parts of the
country saw the advantage of utilizing data collection
and management functions of a larger and more
developed network with an established and staffed
infrastructure. Some of these networks combined
their operations into CoCoRaHS. Over these four
years, active observers grew from 2,000 to over 15,000
(“active” is defined as registered, with a rain gauge
installed and submitting at least one report during
the specified year). This definition was chosen from
a citizen science education perspective, with about
three-quarters of these observers reporting regularly.

2009 survey. Over 7,000 observers took an online
survey conducted in the late summer of 2009 to help
gauge the motivations of CoCoRaHS volunteers, to
determine what they were learning from participa-
tion, and to identify areas for improvement. The
survey helped determine the focus for the next
phase of CoCoRaHS. The survey results pointed out
a need for better cyberinfrastructure and improved
educational materials. It also exposed a relative lack
of diversity among the participants.

new grants from the National Science Foundation’s
Advancing Informal Science, Technology, Engineer-
ing and Math (STEM) Learning (AISL) grant program
and NOAA’s Office of Education provided support for
a multiyear effort to build up the cyberinfrastructure
of the network, to bolster its educational content, and
to attempt to reach broader and younger audiences.

Cyberinfrastructure. The ongoing growth in the num-
ber of observers and data users, and the increas-
ingly large data archive necessitated improvements to the

Fig. 1. CoCoRaHS precipitation map showing daily observations for the period ending 0700 LT 6 May 2015. Precipitation amounts ranged from 0.00 to 7.93 in. (201.4 mm). Total number of reports: 13,030 (many reporting daily) with 6,914 observers measuring greater than a trace.
CoCoRaHS cyberinfrastructure. The need for improved cyberinfrastructure was also driven by new protocols, new data analysis and quality control tools, and improved data mapping and interactions. These improvements, which included a move to dedicated server hardware, performance tuning the database, and more versatile data mapping and graphing tools, led to a significant increase in both performance and capacity of the network.

**Educational/outreach initiatives.** The challenge of bolstering the network’s educational content to improve the public’s climate literacy was next on our list. Several initiatives were undertaken during this period. A webinar series called “CoCoRaHS WxTalk” began in late 2011 ([www.cocorahs.org/Content.aspx?page=wxtalk](http://www.cocorahs.org/Content.aspx?page=wxtalk)). The webinars provide volunteers a chance to link personally to experts in the fields of weather, climate, hydrology, and related fields through presentations with question-and-answer sessions afterward. Many American Meteorological Society (AMS) members have been featured speakers. Topics span the gamut, from clouds, radar, lightning, and severe weather to backyard rainwater harvesting and “So you want to become a Meteorologist?” The webinars are recorded and are available on YouTube.

Another focus was on encouraging weather observers to advance from being weather observers only to also being climate data analysts and investigators. Several data analysis tools were developed to help observers explore their own data and data from other sources. For example, detailed summaries are produced each year at the end of each October–September water year for every station, making it easy to explore daily and seasonal patterns as well as year-to-year and geographic differences ([http://cocorahs.org/WaterYearSummary/](http://cocorahs.org/WaterYearSummary/)).

A natural educational path was to go beyond just precipitation to emphasize the function and importance of the water cycle. A popular YouTube animation on the water cycle was developed in 2013 and has had well over 400,000 views ([https://youtu.be/Z2Y5-NZSzWw](https://youtu.be/Z2Y5-NZSzWw)). Working with a small company in Colorado, we added the measurement of reference evapotranspiration ET, to the CoCoRaHS suite of observations. Motivated observers were encouraged to purchase a fairly inexpensive atmometer (~$220) known as an ETgage ([Gavilan and Castillo-Llanque 2009](http://cocorahs.org/Content.aspx?page=et)) to deploy during the growing season months (Fig. 2). A reporting site was developed along with an in-depth web page on ET ([http://cocorahs.org/Content.aspx?page=et](http://cocorahs.org/Content.aspx?page=et)). This measurement protocol was pilot tested in 2011 and volunteers were recruited in 2012. By 2015, over 130 CoCoRaHS locations across the country were observing ET. A great example of the added value of these reports was the Midwest “flash drought” during the summer of 2012 (Fig. 3). CoCoRaHS observations of rainfall and ET pointed out the quick onset of extreme drought during July and early August, and the rapid alleviation later that summer and autumn. These reference ET data and graphs show clearly the profound differences in water balance around the country, which relates directly to vegetation, landforms, and the number and size of rivers and streams.

During 2012, a partnership was formed with Oregon State University’s Parameter-Elevation Regressions on Independent Slopes Model (PRISM) organization ([Daly et al. 2008](http://prism.oregonstate.edu)). The PRISM-CoCoRaHS Climate Portal was developed that provided CoCoRaHS participants with a sophisticated tool for precipitation analysis and research. CoCoRaHS volunteers were provided exclusive access to estimates of “normal” (recent 30-yr average) precipitation for any location in the contiguous United States as well as gridded estimates of monthly and annual precipitation for any location from 1895 to the present. Volunteers, even if they had only helped collect data for a few months or years, could compare their local observations to regional and historic patterns. The portal helps connect volunteers’ daily precipitation measurements (*weather*) to seasonal patterns, long-term averages, and year-to-year variations (*climate*)—a very important step toward climate literacy. For example, observers hearing of heavy rains in their states could go to the portal and, based on historic data, see how extreme they actually are. CoCoRaHS participants could have a climate reference to compare to for their locations to determine if their recent rainfall totals were greater or less than average, how they compared to wet and dry years of the past, and if there was any evidence of long-term trends in their areas.

To expand the reach of the network to other communities, a guide to climate resources for master gardeners ([http://cocorahs.org/Content.aspx?page=MasterGardener](http://cocorahs.org/Content.aspx?page=MasterGardener)) was developed. The climate guide was used as part of the training materials by several master gardener organizations ([www.extension.org/mastergardener](http://www.extension.org/mastergardener)) across the country, including those in the Colorado State University Extension. Additional outreach to public and community gardens was initiated, resulting in collaborations with the American Horticultural Society and a presentation at the 2014 annual meeting of the American Public Gardens Association in
Fig. 2. ETgage (atrometer) used by selected CoCoRaHS volunteers to measure ET$_o$. (Photo courtesy of Henry Reges.)
Denver, Colorado. A relationship with the National Association of Conservation Districts (NACD) was established in a strategic effort to connect with landowners in rural communities. Precipitation was a natural connection to its mission. There are now many examples—such as Erie County, Ohio; Adams County, Pennsylvania; and Weld County, Colorado—where local conservation districts embraced the need for better local monitoring of precipitation and helped recruit and train dozens of volunteers.

**Leadership/coordination.** A key to growth and sustainability of CoCoRaHS is a strong and motivated corps of regional, state, and local volunteer leaders (coordinators). A focused effort has been made to personally meet, visit, and encourage as many of the local, state, and regional volunteer leaders as possible during travels to conferences and other meetings. In addition, leadership webinars and conference calls have been organized a few times each year. Many coordinators have attended one or more in a series of yearly national workshops on managing and utilizing precipitation observations from volunteer networks sponsored by the Cooperative Extension’s Western Education Extension and Research Activities Committee (Delheimer 2014). This has been a highly effective means for building and maintaining partnerships between states, universities, local organizations, and NOAA’s National Weather Service and National Centers for Environmental Information. It has also cemented the relationship between NOAA’s historic Cooperative Observer Program network (National Research Council 1998) and the more recent and less formal CoCoRaHS.

**CoCoRaHS and schools.** The 2009 CoCoRaHS participant survey showed that our participant demographics consisted mainly of well-educated middle-age to retirement-age Caucasians. As a result, we set goals to reach younger and more diverse audiences. This has proven to be a significant challenge. The most effective approach so far has been targeted outreach to kindergarten through grade 12 schools through the development of educational materials and a “CoCoRaHS Schools” web page (http://cocorahs.org/Content.aspx?page=CoCoRaHS_Schools). In Colorado, 2012 provided a unique opportunity to reach every school with a donated rain gauge during the state’s “Year of Water” celebration (www.cocorahs.org/Content.aspx?page=CoCoRaHS-Schools-Water2012). This statewide campaign allowed us to test various methods for students to collect and enter data, and it helped us to learn how to best disseminate “CoCoRaHS for Schools” to school districts around the country. Nationally, opportunities to reach teachers and school districts continue to expand. As of November 2015, more than 900 schools across the country were registered in the CoCoRaHS.

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**Fig. 3.** 2012 summer water balance for Illinois CoCoRaHS station IL-CP-1. Daily precipitation amounts are shown with blue bars, and daily evapotranspiration rates are shown red with bars. Water balance is shown with a green line. This is the difference between incoming precipitation and outgoing evapotranspiration. Graph depicts occurrence of flash drought during Jul–Aug, when evapotranspiration greatly exceeded precipitation.
database with 550 of them having submitted data (60% participation). Schools are not well suited for continuous year-round participation, but a biannual campaign called “Rain Gauge Week,” where all registered schools are contacted and encouraged to take observations during this time frame, significantly boosts participation.

In late 2012, CoCoRaHS formed an informal partnership with National Aeronautics and Space Administration (NASA)’s Global Precipitation Measurement (GPM) satellite mission’s education and outreach team (http://gpm.nasa.gov/education/rain-engauge) where schools were recruited to take part in a ground validation campaign. Additional funding opportunities in 2014 (Rolston 2015) allowed the targeted recruiting of students in rural Colorado counties by providing gauges and prize incentives for consistent reports. While the quality and continuity of precipitation measurements from schools have been found to be less than from adult backyard volunteers, the educational experience and the diverse participation are highly valued.

**Social media/cellular technology.** To further encourage the participation of broader audiences, the addition of social media (Facebook, Twitter, YouTube) and the development of mobile device applications (apps) were introduced. Mobile device apps not only enticed new observers but older ones as well. Farmers and ranchers, for example, many of whom had not used personal computers or did not have high-speed Internet access in the earlier years of CoCoRaHS are now much more connected by cellular communications. They can immediately record their daily rainfall amounts standing at their rain gauge or while working on their farms and ranches.

**TRAINING.** Training of volunteers is very important to the success of the network and to providing accurate high-quality observations. In the early days of CoCoRaHS in-person training sessions were provided by coordinators on a county-by-county basis. As the network grew and more of our demographic became computer savvy, online training materials were developed. To simplify the training, short topical cartoon animations have been developed. These informative, fun-to-watch "shorts" (Fig. 4) delivered via YouTube (www.youtube.com/user/cocorahs) have helped cover a wide variety of important topics for our new volunteers in a concise and entertaining way. In-person training continues to be useful where volunteer leaders are able to provide it. Continuing education for existing volunteers is delivered in several ways, including the “Message of the Day” (http://cocorahs.org/Content.aspx?page=mod&mod=1) and monthly electronic newsletters (http://cocorahs.org/Content.aspx?page=catch).

**HIGH-QUALITY DATA.** CoCoRaHS from its infancy was never envisioned to be a national and international monitoring network, but it has headed in this direction. The primary reason has been the high quality of data provided by CoCoRaHS volunteers and it has been recognized by data users. Observers are typically highly motivated and interested in accuracy. Furthermore—and this has been very important to the success of the network—the required rain gauge used by CoCoRaHS volunteers—a clear plastic range gauge with a 4-in. diameter and 11.30-in. (287 mm) capacity (Fig. 5)—meets the National Weather Service’s precipitation measurement requirements and is also listed in the World Meteorological Organization’s Catalogue of National Standard Precipitation Gauges (Sevruk and Klemm 1989). This gauge is, by design, a scaled-down version of the NWS historic standard rain gauge. With appropriate care it is effective for measuring all forms of precipitation (rain, hail, and snow) in all seasons of the year. As such, the data can be utilized and combined with data from traditional NOAA official sources, such as the Cooperative Observer Program (COOP) network. Under most circumstances, this type of gauge performs comparably (±4%) when compared to the official National Weather Service’s standard 8-in.-diameter rain gauge that has been used for over 125 years to document our nation’s climate (Doesken 2005). As a result, the data collected by CoCoRaHS have been found to be consistently of high quality and suitable for both climate monitoring and research. Comparisons have been conducted examining how
Fig. 5. CoCoRaHS 4-in.-diameter plastic rain gauge—required equipment for each CoCoRaHS observer. The gauge measures to the hundredth of an inch and has an 11.30-in. (287 mm) capacity, with any amount greater than 1 in. flowing into and collecting in the outer cylinder. The funnel and inner cylinder are removed in cold weather for capturing frozen precipitation. (Photo courtesy of Henry Reges.)
CoCoRaHS data compare with observation from automated gauges. In 2002, an extremely dry year in Colorado, an unpublished comparison showed that the tipping-bucket rain gauges used by the Fort Collins, Colorado, stormwater utility read 10%–20% lower than CoCoRaHS gauges. Some of this bias was attributed to the screens that keep insects and debris from blocking the orifice but which increase undercatch and evaporative loss. More recently, the West Texas Mesonet (www.mesonet.ttu.edu/) systematically compared multiday accumulations collected in the CoCoRaHS gauge with the totals observed from its adjacent automated gauges. It has noted a systematic low bias of its automated gauges when compared to the CoCoRaHS gauge of approximately 5%–10% over a wide range of precipitation amounts (J. Lipe, National Weather Service, Lubbock, Texas, 2015, personal communication). The Urban Drainage and Flood Control District of Denver (http://udfcd.org/) operates an Automated Local Evaluation in Real-Time (ALERT) network of about 200 automated tipping-bucket gauges in the Denver area. It has provided encouragement and financial support for CoCoRaHS since the early 2000s, resulting in a very dense observing network in its target area. The Urban Drainage and Flood Control District uses Weather Surveillance Radar-1988 Doppler (WSR-88D) data in combination with its automated rain gauge data to produce a gauge-corrected product. CoCoRaHS data are then used to independently verify precipitation totals and patterns (http://udfcd.org/wp-content/uploads/uploads/resources/flood%20hazard%20news/FHN_2007.pdf). There

Fig. 6. Comparison of unique CoCoRaHS SWE stations reporting to NOHRSC. Of the SWE reports received, 18% came from CoCoRaHS stations in 2006–07, whereas 58% came from CoCoRaHS stations in 2013–14. (Graphic courtesy of NOHRSC.)

Fig. 7. CoCoRaHS gauge outside the visitor’s dugout at Target Field in Minneapolis, MN. The gauge has a clear, unobstructed view of the sky. (Photo courtesy of Henry Reges.)
are many obvious operational advantages to real-time data from automated networks. However, the added value of spatially dense and consistent quality daily precipitation totals from CoCoRaHS and the National Weather Service’s COOP network help meet the high standards for many climatological and research applications (Burt 2012).

A very important niche that CoCoRaHS fills is measurements of snow accumulation and snow water content. Quantitative measurements of snowfall in the United States have traditionally been limited to National Weather Service cooperative observers, some NWS forecast offices, and several major U.S. airports. Thanks to CoCoRaHS volunteers, who take year-round measurements (about 20% of the CoCoRaHS volunteers take a break during the winter season, but the rest stick with it; Fig. 11), the number of daily snowfall observations in the United States has more than doubled. As with all snow observations, measurements may sometimes be imperfect. But by having many volunteers and greater spatial coverage, it is easier to spot possible errors and biases and, where needed, provide volunteer training.

**USEFUL DATA.** CoCoRaHS volunteers’ observations are making a difference on a daily basis. Survey results have shown that a key reason that volunteers stick with rain gauge observations day after day and year after year is because the data they collect are important and are being put to good use. Observations are immediately made public and observers’ data are ingested in many products on a daily basis. These data provide critical information where it may previously have been lacking, helping scientists and others to continually sharpen their knowledge of precipitation patterns and processes across the country.

Thus, it is excellent for a wide range of uses. Weather forecasters and hydrologists, water managers and research scientists, farmers and ranchers, climatologists, insurance adjustors, engineers, recreationists, and many others, use CoCoRaHS observations regularly. Some specific examples include NOAA’s

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**Fig. 8.** 2013 Colorado flood map with CoCoRaHS stations showing 48-h totals, 0700 MDT 11 Sep 2013–0700 MDT 13 Sep 2013. Analysis based on integrated data from multiple sources, including radar. The dense network of volunteer gauges along the Front Range of Colorado provided a rich resource of precipitation observations for detailed mapping.
River Forecast Centers (RFCs). A critical input to river stage and flow prediction models is mean areal precipitation—the precipitation averaged across a watershed. The more rain gauge reports there are, the more accurately NWS RFCs can assess mean areal precipitation, which equates to better river forecasts. The National Operational Hydrologic Remote Sensing Center (NOHRSC) uses CoCoRaHS data during winter and spring to improve mapping of snow water equivalent (SWE) over North America. Accurate assessment of SWE is essential to supporting effective hydrologic modeling and prediction. Manual measurements of the water content of snowpack are taken by many CoCoRaHS volunteers in snow areas. Core samples of snow on the ground are taken at least once per week and then melted or weighed to determine water content. These data are then combined with SWE measurements taken by some National Weather Service cooperative observers and from extensive automated SWE data collected by the Snow Telemetry (SNOTEL) system [of the U.S. Department of Agriculture Natural Resources Conservation Service (Pagano et al. 2004)] as well as the Airborne Gamma Radiation Snow Survey Program (GAMMA, which makes airborne SWE and airborne soil moisture measurements from low-flying aircraft across the country; Carroll 2001). The result is a robust ground validation dataset that enhances NOHRSC’s remote sensing, snow modeling, and spatial analysis programs. In 2011 over half of the ground-based observations used by NOHRSC came from CoCoRaHS (Fig. 6). One of NOHRSC’s products is the Snow Data Assimilation System (SNODAS) model (Clow et al. 2012). The observations that are incorporated into this model include satellite imagery, airborne remote sensing, and ground-based observations, which include those collected by CoCoRaHS.

Fig. 9. CoCoRaHS map showing 24-h rainfall totals reported by CoCoRaHS observers ending at 0700 CDT 30 Apr 2014. Area includes counties in the Alabama and Florida Panhandles (including Mobile and Pensacola metropolitan areas). Several reports exceeded 18.00 in. (457.2 mm) in 24 hours.
Municipal water providers, such as Denver Water, and regional water managers, including the Lower Colorado River Authority in Austin, Texas, use CoCoRaHS reports daily. CoCoRaHS data help assess available water supplies and current and projected customer demands based on local and regional precipitation patterns and water balance (i.e., during wet periods municipal demand decreases and during dry periods municipal demand increases). Daily observations are important in water management, but so is precipitation accumulated over weeks, months, and seasons. CoCoRaHS observations help by providing these seasonal hydrologic panoramas. Those concerned with agricultural interests, such as the developers of the U.S. Drought Monitor, use not only CoCoRaHS observations in helping chart drought throughout the country, but also reports of drought impacts by CoCoRaHS volunteers (Smith et al. 2014).

CoCoRaHS rain and snow reports are used by hunters, fishermen, snowmobilers, and other outdoor recreationalists. One very interesting recreational use is by Major League Baseball’s Minnesota Twins. During the season the grounds crew keeps a CoCoRaHS gauge mounted near the visitor’s dugout at Target Field (Fig. 7) to help it determine how much rain has fallen on the field and also to access possible poststorm flooding data, which can occur with slow-moving summer storms. During winter, skiing and snowmobilers use CoCoRaHS data and maps to determine where fresh snow has fallen.

There are many examples, from Atlantic tropical storms and Pacific atmospheric rivers to midwestern thunderstorms, where CoCoRaHS has proven to be a great resource in mapping extreme rainfall. In September 2013, unprecedented weeklong rainfall flooded the Front Range of Colorado (Fig. 8). Lives

Fig. 10. Example of one station making a difference. Observer in eastern Comal County, TX, near New Braunfels reporting 7.12 in. (180.8 mm) of precipitation in 24 hours ending at 0700 CDT 6 May 2008, whereas stations nearby received less than 0.1 in. (2.5 mm).
were lost and damage reached into the billions of dollars (Gochis et al. 2015). An army of over 1,000 CoCoRaHS observers helped provide amazing detail for mapping this storm. Other recent extreme event examples captured by CoCoRaHS observers include the Navarro County (Texas) floods of 24 October 2015 [18.95 in. (481.33 mm) in 24 hours], the Palm Beach County (Florida) floods of 10 January 2014 [14.79 in. (375.7 mm) in 24 hours], the Mobile Bay (Alabama)–Pensacola (Florida) extreme event of 30 April 2014 [12.33–18.93 in. (313.2–480.8 mm) in 24 hours] (Fig. 9), and the Islip, New York, flood of 13 August 2014 [13.02 in. (330.7 mm) in five hours]. Finally, in 2008, a New Braunfels, Texas, observer recorded 7.12 in. (180.8 mm) of rainfall in two hours, while stations nearby recorded only 0.1 in. (2.5 mm) or less (Fig. 10). Having a dense, widespread network of volunteers provides amazing detail that might otherwise go undetected. It also provides calibration and validation support for both radar and satellite remote sensing.

A highlight in CoCoRaHS’s history occurred in July 2010, when we learned that our data were being archived by NOAA’s National Centers for Environmental Information (NCEI) and made publicly available as a part of the Global Historical Climatology Network (GHCN)-Daily (Menne et al. 2012). As of December 2014, CoCoRaHS was contributing 25,335 station time series to the GHCN-Daily database. These data can be accessed directly by the public from the National Weather Service website (weather.gov) via “NOWData.”

VOLUNTEER SUPPORT AND SUSTAINABILITY. With an ever-growing network (Figs. 11 and 12), logistical challenges remain (Doesken and Reges 2010). How to most effectively manage large numbers of volunteers spanning the entire country and representing all ages and walks of life—and doing this with only two full-time staff members—is an ongoing question. The excitement of Internet communications in the 1990s and early 2000s helped launch CoCoRaHS nationwide. Direct e-mail and web page communication were very effective in the early years of CoCoRaHS, but they now seem to be waning a bit as more people are burdened with

![Fig. 11. 2010–14 national number of active observers and reports entered. Blue bars show total number of active observers by month. Yellow bars show number of observers who have reported an observation each month. Dashed lines show 12-month averages.](image-url)
excessive e-mail and prefer other forms of social media.

Approximately 260 state and regional volunteer coordinators, primarily made up of professionals from the climate, weather, and water community, help manage the network on a local basis. Sustaining relationships between the coordinators and CoCoRaHS headquarters is imperative. Texas alone has over 1,400 volunteer observers in 254 counties. It is divided into 13 regions with 18 regional coordinators and dozens of county coordinators. Having these local coordinators who know their communities and understand the local weather and climate patterns is very valuable. The local coordinators in each state, although under the CoCoRaHS umbrella, have been given autonomous liberties to shape the program in their state. This has led to the development of creative approaches to volunteer recruiting, engagement, and retention. Newsletters, get-togethers, state web pages, training events, and volunteer recognition vary from state to state; however, without local leadership, it would be much harder to maintain this network.

Figure 11 shows the growth in participation in CoCoRaHS. A recent analysis of our data showed that during the years 2010–13, 71% (19,217 sign-ups; 13,719 making their first report) of those who signed up to join the network made their first report and 71% (9,705 reporting a year later from those 13,719 who made their first report) of those who made their first report were still reporting after one year. In other words, only about half of all initial recruits are still participating a year later. This rate of retention seems discouragingly low, but leaders of other citizen science projects, such as the USA National Phenology Network, are very impressed with CoCoRaHS’s volunteer retention. Also on the bright side, of those who stay with CoCoRaHS for a full year, they are likely to continue for many more years.

On a national level, events like CoCoRaHS March Madness, an annual 31-day recruiting contest in March to win the “CoCoRaHS Cup” (http://cocorahs.org/Content.aspx?page=Marchmadness15), trigger many coordinator interactions between states in the form of friendly competition (Fig. 12). This annual
spring event helps recruit hundreds of new volunteers and helps offset attrition from those volunteers who lose interest, move, or are no longer able to perform the duties of a rain gauge volunteer. Long-established CoCoRaHS states like Colorado, New Mexico, Wyoming, and Texas have observers who have made thousands of reports and have been observers for over 10 years. Still, a comprehensive, nationwide effort to recruit new volunteers is continually needed.

THE FUTURE OF COCORAHS. As CoCoRaHS soon completes its second decade, there are both opportunities and challenges ahead. Automated rain gauge networks are proliferating, supporting real-time hydro-meteorological requirements. The greater accuracy of CoCoRaHS measurements from manually read gauges is still recognized and appreciated but will that be sufficient? CoCoRaHS fills a major observational gap when it comes to snow and hail but will that be supported? Federal grants helped start the network. Now volunteer donations and support from data users are becoming the primary sources for sustaining the network.

CoCoRaHS is interested in helping enhance, develop, and supplement other volunteer observing networks worldwide (Doesken and Reges 2011). Current examples include supplementing observations from NOAA’s Cooperative Observer Program network and developing the 2016 CoCoRaHS expansion across the Bahamas in collaboration with the Bahamas Department of Meteorology through the support of the World Meteorological Organization (WMO), the Global Climate Observing System (GCOS), and NOAA. Expansion on a continental or global scale is technically feasible, but it would only be effective with very strong local interest and leadership. Given time and resources, there are many other opportunities for improvement, including better mapping and data display; more tools for data analysis; research on floods, drought, and climate variability; a revamped web interface; and furthering relationships with collaborators.

CoCoRaHS needs more volunteers. To sign up to become a rain gauge reader, go to the CoCoRaHS website (http://cocorahs.org/) and click “Join CoCoRaHS.” CoCoRaHS data are freely available for research, education, and application. Please direct any questions to info@cocorahs.org.

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REFERENCES


Delheimer, S., 2014: Volunteer precipitation monitoring. Western Association of Agricultural Experiment

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Rolston, K., 2015: Yuma County students to collect precipitation data for CoCoRaHS. Source, Colorado State University, 12 March. [Available online at http://source.colostate.edu/yuma-county-students-to-collect-precipitation-data-for-cocorahs/]


A chaotic attractor at the hurricane maximum intensity stage is captured in an axisymmetric hurricane model, thus suggesting an upper limit on the accuracy of hurricane intensity forecasts at the 4–5-day lead times.

Among various weather systems in the atmosphere, hurricanes possess distinct behaviors due to their approximate axisymmetric structure and thermodynamic feedbacks at the mesoscale, which render their characteristics unique as compared to other atmospheric systems, such as tornadoes, convective cells, and frontal systems. An important result based on this axisymmetry is the well-known steady-state solution for the maximum potential intensity (MPI) that a hurricane can attain under a prescribed thermodynamic condition, which is given by (Emanuel 1986, 2003)

\[ V^* = \frac{C_D}{C_E} \left( \frac{T_s - T_e}{T_e} \right) \left( k_s^* - k_a \right), \tag{1} \]

where \( T_s \) is the sea surface temperature (SST); \( T_e \) is the mean outflow temperature near the tropopause; \( C_D, C_E \) are the surface drag and enthalpy exchange coefficients, respectively; and \( k_s^* \) and \( k_a \) are the moist entropy at the ocean surface and the adjacent atmospheric surface layer, respectively. While the MPI solution [Eq. (1)] has proved to be helpful in a broader context of the hurricane–climate connection under different climate change scenarios or intensity outlooks (e.g., Henderson-Sellers et al. 1998; Knutson et al. 2010; Walsh et al. 2015), it has not been demonstrated whether this steady-state solution is stable. In fact, it would be rather catastrophic if the MPI solution were found to be unstable or if there exist multiple stable points, because this would then imply that the MPI solution cannot be reached and therefore has little practical value. Numerous idealized simulations with either full-physics models or idealized simulations with axisymmetric hurricane models have shown that model-simulated vortices do not settle down to the MPI solution but rather display strong intensity oscillations around the theoretical MPI equilibrium given by Eq. (1) (e.g., Rotunno and Emanuel 1987; Bryan and Rotunno 2009; Hakim 2011, 2013; Brown and Hakim 2013). This poses an important question of whether there exists any limit cycle or an unstable regime that prevents hurricanes from approaching their MPI equilibrium. Of course, the strong variation around the MPI equilibrium could be inherently related to the fact the theoretical MPI solution is valid only under idealized assumptions.
such as the gradient wind balance, rotational axisymmetry, or simplified radial momentum budget in the planetary boundary layer. However, the fact that the MPI solution as given by Eq. (1) could provide a reasonable statistical upper bound of intensity for the majority of observed storms (e.g., Emanuel 2000; Bryan and Rotunno 2009) suggests that the MPI limit does contain important implications about the hurricane intensity equilibrium that the steady-state theory could not reveal.

STABILITY OF MPI EQUILIBRIUM. Stability of the MPI equilibrium was recently examined in a framework of the hurricane-scale dynamics, in which the asymptotical stability of the MPI equilibrium under the wind-induced surface heat exchange (WISHE) mechanism was demonstrated (Kieu 2015). A low-order hurricane-scale model [referred to as the hurricane-scale dynamical (HSD) model] proposed by Kieu (2015) is based on dynamics of several hurricane basic scales, including the scale of the maximum surface wind \( V_m \), the scale of the maximum vertical motion within the inner-core region \( W_m \), and the scale of the warm anomaly in the eye center that is represented by buoyancy variable \( B_m \). The essence of this HSD model is that these scales are not independent but strongly governed by the hurricane dynamics and thermodynamics, which can be shown to evolve in time according to the following set of nondimensionalized constraints:

\[
\begin{align*}
\dot{v} &= v w - v^2, \\
\dot{w} &= -s v^2 + sb, \\
\dot{b} &= -b w + v^2 - \kappa b,
\end{align*}
\]

where \( v, w, \) and \( b \) denote nondimensional values of \( V_m, W_m, \) and \( B_m \), respectively; \( s \) is a parameter representing the squared ratio of the depth of the troposphere to the depth of the planetary boundary layer; and \( \kappa \) is a constant representing the Newtonian cooling. An interesting property of this HSD system is the existence of a unique stable critical point given by \( v = (1 - \kappa/2), \ w = (1 - \kappa/2), \) and \( b = (1 - \kappa/2) \) for \( \kappa \sim O(10^{-1}) \), which corresponds indeed to the MPI equilibrium [in the absence of radiative cooling, the point \( v = 1 \) corresponds exactly to \( V_m \) given by Eq. (1); see Kieu 2015]. Examination of the local stability of this critical point shows that although the radiative forcing could modify the basin of the attraction toward the MPI equilibrium, the equilibrium is structurally stable and is a hyperbolic sink; all neighbors of the MPI will converge spirally to the MPI equilibrium regardless of the vortex’s initial conditions (Fig. 1).

Despite the simplicity of the HSD model, two significant implications follow from the resulting MPI stability. First, the MPI equilibrium should no longer be characterized just in terms of \( V_m \) (i.e., \( v = 1 \)) as often presumed in previous studies, but it should take into account conditions for both the warm-core anomaly \( b = 1 \) and the vertical motion in the central storm region \( w = 1 \) as well. This strong constraint among the three scales \( (v, w, b) \) explains why a slight perturbation in the warm-core anomaly or fluctuations in the secondary circulation can easily cause a hurricane’s intensity to oscillate strongly around the equilibrium, even when \( V_m \) matches exactly the MPI value. Such a constraint in the hurricane scales may also justify why the theoretical MPI has never been captured in previous numerical simulations, which inherently contain many sources of vertical motion perturbations and temperature anomalies.

Second, the unique sink of the HSD system implies that the hurricane end fate is nothing but a stable point, which is determined by the large-scale environment regardless of the initial conditions. As a demonstration of the stability and the uniqueness of the MPI equilibrium, Fig. 1 shows the flow orbits obtained from numerical integrations of the HSD system [Eqs. (2a)–(2c)] with several different initial conditions; all are indeed spirally attracted toward the MPI equilibrium located at the point \( (1,1,1) \) in the phase space of \( (v,w,b) \). Of the four example orbits, note in particular the strong initial wobbling of the red orbit for which the initial value of \( V_m \) is set equal to the exact MPI value [i.e., \( v(0) = 1 \)], but the initial warm anomaly \( B_m \) is half of the critical value [i.e., \( b(0) = 0.5 \)]. This specific case resembles a situation in which one initializes a hurricane model with an initial vortex whose \( V_m \) matches the observed intensity, but the initial warm anomaly at the core of the vortex is not consistent with the wind structure. In
this scenario, it is expected that the vortex would experience a rapid adjustment before approaching the maximum intensity limit similar to that seen in Fig. 1, thus resulting in large initial intensity errors. Despite this initial adjustment, the final stage of the hurricane development is still the same MPI equilibrium as dictated by the HSD system as long as the large-scale conditions are conducive to the hurricane development.

Of interest is that the existence of the unique MPI sink could shed light on a standing issue in current operational hurricane models, which all exhibit rapid growth of intensity errors during the first 36–48 h, but the intensity errors saturate quickly after 3 days regardless of numerical models or initial conditions. Figure 2 shows an example of verification of real-time intensity forecasts in the northwestern Pacific (WPAC) basin for five different operational models during 2012–14. Here, the verification for the WPAC basin is presented because of the larger sample size of strong storms that will facilitate our subsequent analysis of the MPI limit and chaotic attractor. Except for the Naval Global Environmental Model (NVGM), which possesses an initial intensity error as large as the 4–5-day errors, all other models display the most rapid intensity error growth during the first 48 h despite very different vortex initial conditions and numerical modeling systems. In light of the HSD dynamics, such behavior is a consequence of the fact that the hurricane development does not have any other choices. As soon as favorable conditions for the hurricane feedback are ensured, an initial vortex will be forced to approach an MPI limit at which its absolute angular momentum can be balanced by the frictional forcing. Because of this convergence of hurricane intensity toward the same equilibrium even along highly different orbits, the rate of the intensity
error growth will be gradually flattened out at longer ranges as seen in Fig. 2.

It should be noted that for real storm development, it is almost certain that few, if any, storms could eventually reach their MPI due to continuous changes in the ambient environment. However, as long as the hurricane's intensity approaches the same intensity limit, both the forecasted and observed intensities will ultimately converge, and the intensity errors will therefore diminish at longer ranges. Such convergence toward the MPI equilibrium justifies the fact that various idealized experiments in previous studies with considerably different vortex initial strengths, structures, and approximations all share a similar hurricane structure at the mature stage (see, e.g., DeMaria and Schubert 1985; Rotunno and Emanuel 1987; Wang 2001; Hendricks et al. 2004; Yang et al. 2007; Bryan and Rotunno 2009). From this perspective, the existence of the unique MPI stable point is noteworthy, as it implies that a hurricane's intensity and structure depend more on the large-scale environment at the longer ranges than on the hurricane's initial conditions.

CHAOTIC MPI ATTRACTOR. While the stable and unique MPI equilibria may justify the slower rate of error growth at the long lead times as discussed above, the intensity errors at 4–5-day lead times do not approach zero as would be expected if the MPI equilibria were truly unique. Instead, the 4–5–day intensity errors are consistently around 8–10 m s\(^{-1}\) as seen in Fig. 2, for which the HSD system cannot explain. From a practical standpoint, such intensity errors are apparently unavoidable even in the framework of the hurricane-scale dynamics because of several factors, such as the constant movement of hurricanes under large-scale environmental steering flows, dry-air intrusion, strong vertical wind shear, and landfall, which cuts off the energy input. Therefore, the MPI has to continuously adjust to the new environment such that hurricanes may have little chance to settle down to their equilibrium. On the other hand, the long-range errors may be related to some hidden chaotic nature of the MPI equilibrium in higher dimensions that the low-order hurricane-scale framework cannot account for due to the lack of detailed processes in the HSD model, such as cloud radiative feedback, microphysics, and small-scale dynamical processes.

To address the relative impacts of the large-scale fluctuations on the MPI stability versus potential existence of a chaotic attractor in a more general setting, a full-physics axisymmetric model developed by Rotunno and Emanuel (1987, hereinafter the RE model) is used for a set of 1,000–day simulations (see supplement for the description of the RE model: http://dx.doi.org/10.1175/BAMS-D-15-00168.2). For such a full-physics model with ~5 × 10\(^3\) degrees of freedom,\(^3\) it is no longer feasible to expect a single equilibrium point for orbits to settle down. Instead, the most optimistic scenario for such a high-dimension model is that the model would display an attracting set that the hurricane orbits will approach after some period of time instead of a pointlike attractor. The reason behind such expectation of an attracting set at the MPI equilibrium in full-physics models is because

Fig. 2. Verification of the real-time hurricane intensity forecasts (m s\(^{-1}\)) in the WPAC basin during 2012–14 for the HWRF model (red), the U.S. Global Forecast System model (GFS; black), NVGM (purple), the Princeton GFDL model (cyan), and the COAMPS-TC model (blue). Numbers below each forecast lead time denote the number of cases verified. Error bars denote 95% confidence intervals.
numerical models often implement numerous upper/lower bounds for different physical parameterizations, such as the radiative forcing caps, truncated tendencies and forcings, or the maximum lapse rate, to ensure the model stability. In this sense, numerical models are genuinely a bounded dynamical system. In addition, various averaging or filters that act as absorption of unrelated waves could render the numerical models dissipative after sufficiently long integration. Viewing from this perspective, the existence and closure for the bounded attracting sets are fully ensured (Ott 2002), and it is thus natural to expect that the full-physics model should display a finite-volume attracting set rather than a pointlike attractor as dictated by the HSD system. Whether this type of an attracting set could possess chaotic features is an issue that depends further on the denseness property and the existence of positive Lyapunov exponents, which may be specific to each individual model, physical parameterization, boundary treatments, or model vertical and horizontal resolution.

Because it is impossible to represent flows in the phase space of dimension \( \sim 5 \times 10^4 \), Fig. 3 shows the flow orbits in a reduced phase space consisting of the three fundamental scales \( V_m, W_m, \) and the maximum temperature anomaly at the vortex center \( T_m \). Here, different colors in Fig. 3 represent a set of 1,000-day simulations with different vortex initial intensities, which ranges from \( V_m = 12 \) to 50 m s\(^{-1}\). Such representation of the flow orbits in the reduced space is meaningful because the denseness of any chaotic attractor ensures that its projection onto a subspace is also chaotic (Lorenz 1963; Ott 2002). While there is no single pointlike attractor as anticipated, it is seen in Fig. 3 that all orbits are quickly pulled toward a specific region in the phase space of \( (V_m, W_m, T_m) \) due to the bounded property of the RE model, with its center located roughly at \( V_m \sim 66 \) m s\(^{-1}\), \( W_m \sim 5 \) m s\(^{-1}\), and \( T_m \sim 20 \) K (referred to as the MPI attractor\(^4\)). One notices also the strong wandering of the vortex intensity during the first several days into integration with \( V_m \) reaching as high as 100 m s\(^{-1}\) before settling down to the MPI attractor, which is somewhat similar to the intensity variation in the low-order model (cf. Fig. 1). The large fluctuation in the vortex intensity during the transient period, often linked to the supergradient intensity, is seen even for the case with initial \( V_m = 50 \) m s\(^{-1}\) (green dots), which is fairly close to the MPI limit of \(~66 \) m s\(^{-1}\). Such an initial adjustment is likely because the RE model vortex is initialized with a simple vortex structure that has the tangential wind maximum at the surface and linearly decreased upward, and the temperature anomaly derived from the thermal wind relationship, whereas the initial secondary circulation is not taken into account (Rotunno and Emanuel 1987). In light of the low-order HSD model, this vortex initialization produces an initial inconsistency among \( V_m, W_m, \) and \( B_m \), and the vortex intensity thus varies strongly before approaching the quasi-equilibrium stage.

Unlike the Lorenz attractor that swiftly exhibits beautiful butterfly wings after a few hundred iterations (Palmer 1993), one further notices in Fig. 3 that there is no limit cycle or any specific fractal structure for the MPI attractor in the RE model, even after a long integration of 1,000 days. Instead, flows in the RE model are trapped within a volume depicted by the cloud of points in the phase space of \( (V_m, W_m, T_m) \) with a size of \(~8 \) m s\(^{-1}\) as projected onto the \( V_m \) dimension regardless of the initial vortex conditions (here, the size of the attractor is defined as a standard deviation with respect to the 1,000-day mean value; cf. Figs. 3 and 4a).

The convergence of different initial conditions toward the same MPI attractor in the RE model is consistent with the conclusions drawn from the HSD model (cf. Fig. 1) and contains significant implications for the hurricane predictability limit. Recall from Lorenz’s definition of the range of predictability as the time interval within which forecast errors would not exceed the difference between randomly chosen states. As shown in Fig. 3, such a difference according to Lorenz’s definition is \(~8 \) m s\(^{-1}\) for experiments with very different initial vortex conditions, and so the limit of \( 8 \) m s\(^{-1}\) in this sense could indeed represent the intensity error saturation in the RE model as defined by Lorenz (1969). Of course, the four experiments shown in Fig. 3 may not fully characterize the entire set of randomly selected initial states, but they could well cover the variation of the vortex initial intensity for practical purposes. In fact, our sensitivity experiments with many different combinations of initial conditions in the RE model do exhibit the same MPI attractor (not shown), thus suggesting the limit of \( 8 \) m s\(^{-1}\) as an error saturation threshold in the RE model, below which the intensity error cannot be reduced further by improving the model’s initial conditions.

Of significance is that the overall boundedness and denseness of the volume surrounding the MPI equilibrium gives us a hint that this MPI attractor may possess sensitive dependence on initial

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\(^4\) Technically, an attractor contains more structure than the attracting set. In this study, we will refer to the attracting set displayed in Fig. 2 later as an MPI attractor, based on an assumed denseness of the flow orbits in the RE model.
conditions, which could inhibit us from reducing the hurricane intensity errors after hurricanes enter their MPI regime.

To shed light onto the initial condition sensitivity inside the MPI attractor in the RE model, the leading Lyapunov exponent is numerically estimated for 500 cycles starting after 5 days into integration, when the simulated vortex roughly reaches its statistical equilibrium (Fig. 3a). Here, the leading Lyapunov exponent is defined as

\[
\lambda_m = \lim_{\tau \to \infty} \frac{1}{\tau} \ln \left( \frac{\|v^{(m+\tau)} - v^{(m)}\|}{\|v^{(m)}\|} \right),
\]

where \(v = (u, v, w, T, q)\) is the model state vector; \(\epsilon\) is a perturbation vector; \(v^*\) is the perturbed state; \(\|\|\) is the energy norm, which is defined as

\[
\|v\| = \sqrt{u_i^2 + v_i^2 + w_i^2 + c_R T + L_v q_i}
\]

with the index \(i\) running over all the model's grid points; \(T_w = 500\) days; \(\epsilon_{\infty}\) is a prescribed numerical limit of the perturbation scale at each iteration; \(\tau = 3\) h is a fixed time interval for cycling the perturbation; and the subscript \(m\) indicates the \(m\)th number of iterations. Technically, \(\epsilon_{\infty}\) needs to approach zero as \(T_w \to \infty\). Because of the numerical limitation with perturbation imposed on the flow trajectory inside the MPI attractor will amplify with a factor of \(\sim e^3\) and soon spread out over the entire attractor space after approximately 3 h into integration. A direct consequence of this finding is that any fluctuation in the ambient environment after a storm reaches its mature stage could quickly produce as large of a variation in the storm intensity as the entire attractor space after just a few hours. From the standpoint of numerical model forecasts, this means a small perturbation introduced to hurricanes at their mature stage will lead to strong fluctuation in a hurricane's intensity, and there is no effective way to prevent this intensity fluctuation. As a result, there appears to be little hope of controlling the hurricane intensity error once they enter their MPI attractor, at least from the perspective of the RE model.

The chaotic property of the MPI attractor demonstrated in Fig. 4 leads to an intriguing dilemma. On one hand, the existence of the MPI attractor implies that any small change during the early stages of the storm development will not generally have much of an impact on the later hurricane development; all vortex initial conditions will be pulled toward the MPI attractor after some period of time. Such an MPI attractor has some real implication to the development of numerical models, as this demonstrates that
a hurricane’s intensity in a numerical model will not increase indefinitely but tend to approach a limit regardless of how we initialize models, implement new physical parameterization schemes, higher model resolution, or different numerical algorithms. Basically, the model states will be trapped inside an attractor whose characteristics are determined by the large-scale environment instead of storms’ initial conditions.

On the other hand, the chaotic nature of the MPI attractor suggests that any small fluctuation in the large-scale environment will rapidly drift the hurricane’s intensity away, with intensity variations as large as the entire MPI attractor space. There is no simple way to control such intensity fluctuation. For example, a small perturbation of a wind component of 0.5 m s\(^{-1}\) will amplify to as large as 9 m s\(^{-1}\) in just 3 h according to the RE model. This may justify the constant range of the 8–10 m s\(^{-1}\) intensity errors at the 5-day lead time during the last 30 years as seen in Fig. 2, despite the significant reduction in the track forecast errors. In this sense, the chaotic property of the MPI attractor imposes a true upper bound on our future effort of improving the accuracy of hurricane intensity forecasts.

REAL-TIME REALIZATION. Although the RE model could provide an estimate for the intensity error saturation of ~8 m s\(^{-1}\) at the mature stage, how this error saturation is further realized and interpreted for real-time intensity predictability requires further examination. Understanding the implication of such error saturation to the range of the predictability limit in real-time intensity forecasts will directly address an important question of how far into the future a dynamical model can predict the hurricane’s intensity. While Lorenz (1969) suggested a 2-week range for an initial error to approach an error saturation limit in the two-dimensional barotropic flow framework, this 2-week limit turns out to depend critically on the underlying assumption of the basic energy spectrum. Recent studies by Rotunno and Snyder (2008), Durran and Gingrich (2014), and Judt et al. (2016) indicated that a simple change from the \(-5/3\) spectrum to the \(-3\) spectrum of the background energy could result in a radical shift from limited to unlimited predictability. With the unique rotational dynamics of hurricanes, it is thus natural to expect a much different range of predictability for hurricane intensity forecasts from the general 2-week limit obtained in Lorenz’s (1969) model.

Before interpreting the chaotic MPI attractor obtained from the RE model for real-time intensity errors, it should be recalled that real-time forecasts by operational models contain statistics of all cycles with different storm initial intensities at all stages of development instead of monotonic growth from the beginning to the maximum intensity limit as in idealized experiments. In addition, real hurricanes constantly move into colder SSTs and stronger vertical wind shear at higher latitudes or simply make landfall, and so often weaken rapidly before even entering the MPI attractor if they move too fast or are too close to coastlines. In this regard, the real-time 4–5-day intensity errors do not always imply the errors inside the MPI attractor. To reduce the negative impact of the mixed-cycle statistics on the predictability limit in real-time verification, Fig. 5 shows the verification of a hurricane’s intensity similar to that shown in Fig. 2, but the verifications are carried out only for cycles with the observed initial intensity of category 2 and above (i.e., \(V_m \geq 47 \text{ m s}^{-1}\), or ~95 kt). Such an initially strong intensity stratification is to ensure that hurricanes approximately enter their MPI
Note that this selection of initially strong storms in the real-time verification does not entirely eliminate cases in which the real hurricanes weaken too quickly as they move into colder SST or make a landfall. Nevertheless, it could at least highlight the growth of intensity errors of strong storms that we can at most infer inside the MPI attractor from real-time forecasts at present.

It is seen in Fig. 5 that while the five models behave differently at first, all models quickly converge to a similar intensity error of ~8 m s\(^{-1}\) after 3 days. The strong intensity variations obtained from the RE model and the HSD model offer a hint for this real-time intensity error growth. Specifically, for the global models whose initial hurricane intensity is much weaker than the observed intensity, the hurricane initial states are essentially outside the MPI attractor (i.e., the initial vortex intensity is too weak). As a result, they will be immediately pulled into the MPI attractor, thus accounting for the decrease of the intensity errors during the first 3 days into integration, similar to the behaviors drawn from the HSD model (Fig. 1) and the RE model (Fig. 3). Because of the finite volume of the MPI attractor, the hurricane states are subsequently trapped in the MPI attractor, and their intensity errors are thus bounded. Given that the size of the MPI attractor as projected onto the \(V_m\) dimension is ~8 m s\(^{-1}\) as obtained from the RE model, one can see that the 8 m s\(^{-1}\) limit appears to be indeed realized for these global model forecasts.

For the regional models that employ a vortex initialization procedure to match the initial intensity with the observed intensity, the intensity errors also spread out rapidly over the entire MPI attractor after ~25 h into integration. Although the error growth in the regional models is less than that in the global models, the rapid intensity error growth during the transient period in all regional models is an indication that the consistency among \((V_m, W_m, B_m)\) may not be ensured during the vortex initialization process, which leads to strong wandering of the model state, similar to what is shown in Figs. 1 and 3. Note that unlike the error growth in the Hurricane Weather Research and Forecasting (HWRF) Model, whose intensity does not experience a surge in error growth during the first 12 h probably due to its balanced bogus vortex technique (Tallapragada et al. 2014b), the more rapid error growth in the other two regional models is likely because these models seem to constrain only the maximum surface wind to match the observed \(V_m\) rather than the full vortex structure. As such, the initial hurricane states in the Geophysical Fluid Dynamics Laboratory (GFDL) model and the tropical cyclone version of the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS-TC) model may be actually far from the MPI attractor (in the dimensions of \(W_m\) and \(B_m\)), thus giving rise to the rapid error growth before spiraling toward the MPI attractor similar to the experiments with the HSD model and the RE model. Of course, the above-mentioned explanations of the error growth in both the regional and global models are more or less speculative until more detailed analyses of the dynamics for each individual model are examined. However, the general behaviors of the rapid error growth and the subsequent saturation in these operational models at the

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\(^{5}\) Given the absolute intensity errors in the range of 8–10 m s\(^{-1}\), the intensity threshold that represents more accurately the lower bound of the MPI attractor would be in the range of 55–57 m s\(^{-1}\) (category 3 and above). Because of the limited sample size, the threshold of 47 m s\(^{-1}\) is chosen for the strong storm verification in this study. Verifications for a higher threshold of 55 m s\(^{-1}\) give similar results as shown in Fig. 5, except for a smaller number of verified cases and so are of less statistical significance.
same limit of 8 m s\(^{-1}\) after approximately 3 days are quite consistent with both the RE and HSD models, thus offering new insight into the error growth issue in operational models.

From the perspective of real-time error growth shown in Figs. 2 and 5, these verifications demonstrate an important aspect of the intrinsic predictability limit of the hurricane’s intensity. If one takes the limit of 8 m s\(^{-1}\) obtained from the RE model at face value as a real-time error saturation threshold, it is immediately suggestive from Figs. 2 and 5 that it would take less than 3 days for hurricanes to approach this error saturation limit in real-time intensity forecasts. In fact, Fig. 5 shows further that it takes even less time (~20–27 h) for hurricanes to reach this error saturation level once they are of category 2 and above, which is again consistent with the chaotic property of the MPI attractor demonstrated in the RE model. Therefore, we speculate that the 3-day interval is likely the maximum range that a dynamical model could be most skillful in predicting hurricane intensity. After the 3-day limit, the intensity errors will stay at ~8 m s\(^{-1}\) at longer ranges, provided that the environmental conditions are sufficiently favorable for the error saturation limit to reach this saturation threshold. Of course, this postulation is by no mean conclusive, as it is based on the error saturation of the maximum tangential wind error that may not reflect the entire TC dynamics. One could have a longer predictability range for forecasts of, say, the intensity tendency or the rapid intensification. However, addressing such different aspects of intensity forecasts would require much more in-depth investigation of TC dynamics than what is presented in this study.

Despite the consistent behaviors of the real-time intensity error growth with those inferred from the HSD and RE models, we should point out that the above-mentioned real-time error growth analysis contains some inherent uncertainties due to several factors, such as a limited sample size, a lack of detailed analyses of the model vortex’s initial condition, inadequate representation of hurricane physics, and even discrepancies between the model pointwise maximum surface wind and the observed intensity. Furthermore, our real-time error analysis in Fig. 5 is only for the initially strong storms of category 2 and above. A caveat of this real-time statistics for initially strong storms is that once hurricanes reach category 2 and above, rarely do they sustain high intensity for five full days, because in most cases they weaken quickly due to making landfall or curving to a more hostile environment at higher latitudes. Therefore, the intensity statistics for the initially strong storms at lead times longer than 3 days is heavily influenced by landfalling and other unfavorable conditions, and one should be therefore cautioned when judging the statistics of the intensity errors beyond the 3-day lead time for strong hurricanes.

As a final note, we should mention that, unlike the behaviors of strong storms, whose states are close to the MPI attractor, an initially weak storm may have distinct error growth characteristics, which are related to the transient orbit and so differ fundamentally from the error growth inside the MPI attractor (Lorenz 1963). This explains the longer time interval needed to reach the error saturation shown in Fig. 2 (~3 days) than what is shown in Fig. 5 (~1 day). Such error growth, which is related to transient orbits in real-time forecasts, requires more analyses of flow orbits than a few simple statistics, and it is not examined herein due to our lack of linear tangential models.

**DISCUSSION.** While the existence of a chaotic MPI attractor imposes a limit of ~8–10 m s\(^{-1}\) on the hurricane intensity errors at the range of 4–5 days, there is still a question of whether this is a true value for the hurricane intensity error saturation. Previous studies have shown that such intensity error saturation may depend on specific environmental conditions, the type of numerical models, or physical approximations. For example, a 300-day idealized experiment in the study by Hakim (2011) using a different axisymmetric model captured intensity variation as large as 12 m s\(^{-1}\) at the statistical equilibrium, whereas numerical simulations with a full-physics model by Yang et al. (2007) exhibited a smaller variation of ~7 m s\(^{-1}\) at the mature stage (cf. Fig. 1 in Yang et al. 2007). Likewise, real-time statistics of the HWRF Model shows slightly smaller 4–5-day errors in the eastern Pacific basin (7–9 m s\(^{-1}\)) and in the North Atlantic basin (8–10 m s\(^{-1}\); Tallapragada et al. 2014a). Despite these ranges of intensity error saturation limit in different basins and modeling systems, it is important to note that the convergence of the absolute intensity errors in the range of 8–10 m s\(^{-1}\) from different models and real-time statistics suggests that we are likely close to a true intensity error saturation limit below which the intensity error may not be reduced further after 4–5-day lead times.

Given the intensity error saturation of ~8 m s\(^{-1}\) as drawn from both the RE model and real-time experiments, it is important to note that this error saturation alone is not sufficient to determine the range of predictability. In principle, it is possible that hurricane development may take a long time to reach a saturation threshold and so the existence of the error
saturation does not contain information of how long the saturation level will be reached. Furthermore, the 8 m s⁻¹ limit is obtained under an assumption that favorable environmental conditions for hurricane development are well maintained such that the MPI attractor could be realized. In this regard, the limit of 8 m s⁻¹ simply establishes an intrinsic intensity difference that two arbitrarily different initial vortex states would have at the maximum intensity stage.

It should be also mentioned that the range of hurricane intensity predictability, which is defined here as a time interval for an initial intensity error to approach the error saturation of 8 m s⁻¹, may vary from about 3 days at the early developing stage to less than 1 day at the mature stage. Such an estimation of the range of predictability of about 3 days is not derived or proven by any model; it is merely obtained from the statistics of real-time intensity forecasts, similar to the 2-week limit in Lorenz’s model that is obtained from the assumption of an empirical –5/3 spectrum. This 3-day range of predictability is consistent with recent error variance analysis from a linear inverse model by Hakim (2013), which also suggested a limit of 3 days for forecasts of tangential wind at the quasi-stationary equilibrium stage. Based on these results, it is rational to postulate that

1) the 8 m s⁻¹ error is close to a lower bound of the absolute intensity errors at 4–5-day lead times that we may not be able to reduce further in the future; and

2) the maximum range of predictability of hurricane intensity is about 3 days.

We emphasize again that the above postulation of a 3-day predictability limit is solely from the perspective of intensity absolute errors. It is possible that forecasts of the phase of hurricane development such that the rapid intensification or the rapid weakening can be more predictable. Likewise, a specific numerical model may have a longer or shorter range of predictability, depending on each model system design and configuration, that we need to examine individually.

Although our result suggests that improving the hurricane intensity at the 4–5-day lead times ought to focus more on the large-scale environment, we by no means dismiss the importance of the vortex’s initial condition. This is because an initially too-weak or too-strong storm could certainly determine the subsequent feedback in some specific situations. For example, a too-weak storm could be sheared off quickly during initial development, such that the WISHE feedback might not have enough time to become effective, or that dry-air intrusion could severely interfere with the storm’s development with the result that the necessary equilibrium mechanisms could never be applied. The conclusion in this study about the longer-range control of the environment to the hurricane development is under an implicit assumption of well-maintained favorable conditions for hurricanes to develop, and it should be interpreted therefore from the statistical perspective instead of from the development of a single storm.

ACKNOWLEDGMENTS. We thank Greg Hakim (University of Washington), two anonymous reviewers, and Editor Chris Landsea for their constructive comments and suggestions, which helped improve the presentation of this manuscript substantially. This research was supported by the start-up fund provided by Indiana University in Bloomington, Indiana, and partially by the NOAA Hurricane Forecast Improvement Program (HFIP).

REFERENCES


AMS titles now available as eBooks at springer.com
An observation and modeling campaign in the Bay of Bengal is aimed at studying upper-ocean and lower-atmosphere processes and interactions in relation to Indian Ocean monsoons.

The climate of the tropical ocean and atmosphere is set by monsoons, associated with large-amplitude shifts in the intertropical convergence zone induced by the seasonal cycle of solar insolation with differential heating over the land and ocean. Arguably, the most striking and intense monsoon is the Indian Ocean monsoon (IOM), which drastically affects the livelihoods of more than a billion people in Indian Ocean rim nations (Gadgil 2003).

The large-scale pressure gradients that drive the IOM are strongly modified by air–sea interactions, leading to pronounced subseasonal variability, particularly in the Bay of Bengal (BoB; e.g., Schott and McCreary 2001). This region has been the focus of several previous field campaigns aimed at air–sea interaction and monsoon variability (e.g., Bhat et al. 2001; Webster et al. 2002; Rao et al. 2011). For example, the Bay of Bengal Monsoon Experiment (BOBMEX) examined organized convection using data collected during July–August 1999 (Bhat et al. 2001). The Joint Air–Sea Monsoon Interaction Experiment (JASMINE) addressed intraseasonal and interannual variability of the monsoon in the eastern Indian Ocean spanning 5°S–15°N (Webster et al. 2002). The Indian government research program, continental tropical convergence zone (CTCZ), investigated intraseasonal variability and monsoon break cycles using observations collected in the northern BoB in July–August 2009 (Rao et al. 2011). Collectively, these studies have improved our understanding of ocean–atmosphere processes in this region; however, significant gaps in our understanding remain, particularly in relation to the role of small-scale ocean processes in ocean heat and freshwater fluxes and in air–sea interaction.

Understanding and prediction of the spatiotemporal evolution of the BoB upper-ocean structure and its linkage to the northern Indian Ocean (IO) has been impeded because of uncertainty in the freshwater distribution, set by high rainfall and river runoff. Since shallow, salinity-controlled mixed layers (MLs) have a strong influence on the distribution of upper-ocean
heat content and sea surface temperature (SST), determining the mixing pathways of river runoff and quantifying the upper-ocean freshwater budget are a priority. The importance of freshwater inputs and formation of shallow mixed layers for the monsoon has been previously noted by Shenoi et al. (2002), and Rao and Sivakumar (2003) made a first-order attempt to quantify the sea surface salinity budget on a seasonal basis using historical hydrophysical fields. At the basin scale, circulation and advection of salinity are strongly controlled by wind and remote equatorial forcing [Schott and McCreary (2001), Shankar et al. (2002), Jensen (2001, 2003), Vialard et al. (2009), Durand et al. (2009), Girishkumar et al. (2013), Vinayachandran et al. (2013), Yu et al. (1991), Potemra et al. (1991), and Yu and McPhaden (2011) are a few references out of many]. The monsoon-driven, seasonally reversing currents alternately export low-salinity BoB water into the Arabian Sea (AS) via the East India Coastal Current (EICC) and Winter Monsoon Current (WMC) and import saltier Arabian Sea water into the BoB via the Summer Monsoon Current (SMC; e.g., Murty et al. 1992; Schott et al. 1994; Shetye et al. 1996; McCreary et al. 1996; Schott and McCreary 2001; Jensen 2001, 2003; Durand et al. 2009; Vinayachandran et al. 2013; Mukherjee et al. 2014). Monsoonal forcing also induces energetic mesoscale and submesoscale features, which complicate the regional oceanographic circulation, and, consequently, it is not completely clear how the BoB and Arabian Sea interact with each other and with the Indian Ocean equatorial region in distributing freshwater. Furthermore, the details of how upper-ocean processes regulate the freshwater distribution and influence air–sea interactions are poorly understood. Improving the predictability of coupled air–sea models requires a more detailed understanding of the space–time variability of the BoB and physical parameterizations that accurately capture relevant mesoscale and small-scale physics. The initiative Air–Sea Interactions in the Northern Indian Ocean (ASIRI) is a direct response to this need. ASIRI addresses regional-scale air–sea interactions, atmospheric boundary layer structure, and ocean circulation in the BoB using both the observations and numerical models (Lucas et al. 2014). ASIRI combines the first concurrent field observations of small- to regional-scale ocean observations spanning the entire BoB over multiple seasons with high-resolution air–sea coupled modeling.

Facilitated by the Office of Naval Research, ASIRI melds the resources of partner country initiatives, which include the Ocean Mixing and Monsoons (OMM) program of the Monsoon Mission of India, the Coastal Currents Observations Program (CCOP) of the National Aquatic Resources Research and Development Agency (NARA) of Sri Lanka, the Effects of Bay of Bengal Freshwater Flux on Indian Ocean Monsoon (EBOB) program of the U.S. Naval Research Laboratory, and Remote Sensing of Atmospheric Waves and Instabilities (RAWI), a joint initiative between the United States, NARA, Seychelles, Singapore, and the U.S. Army Research Laboratory (ARL). Here we describe the initial findings of the ASIRI project, focusing on ocean observations. In addition, marine mammal observations were conducted (described in the sidebar “Marine Mammal Observations”).

**SCIENTIFIC RATIONALE AND OBJECTIVES.** ASIRI’s primary aim is to understand the dominant mesoscale and submesoscale processes that determine the freshwater distribution, including transport and mixing terms, and to determine the influence of upper-ocean structure on air–sea interactions regulating the freshwater flux. Concurrent field observations allow ASIRI to target these scientific objectives through a holistic, interdisciplinary approach that integrates observations and modeling over multiple seasons with high-resolution air–sea coupled modeling. This approach leverages the resources of partner country initiatives, such as the OMM program of the Monsoon Mission of India, the Coastal Currents Observations Program (CCOP) of the National Aquatic Resources Research and Development Agency (NARA) of Sri Lanka, the Effects of Bay of Bengal Freshwater Flux on Indian Ocean Monsoon (EBOB) program of the U.S. Naval Research Laboratory, and Remote Sensing of Atmospheric Waves and Instabilities (RAWI), a joint initiative between the United States, NARA, Seychelles, Singapore, and the U.S. Army Research Laboratory (ARL). The project aims to advance understanding of air–sea interactions and their role in freshwater distribution over the Northern Indian Ocean, a region of significant biogeochemical and ecological importance. The collaboration among partner countries and institutions fosters international cooperation and learning, enhancing the scientific outcomes and applicability of the research.

**AFFILIATIONS:** Wijesekera, JAROSZ, JENSEN, TEAGUE, and WANG—Naval Research Laboratory, Stennis Space Center, Mississippi; SHROYER and NASH—Oregon State University, Corvallis, Oregon; TANDON, RAMACHANDRAN, and BUCKLEY—University of Massachusetts Dartmouth, Dartmouth, Massachusetts; RAVICHANDRAN—Indian National Centre for Ocean Information Systems, Hyderabad, India; BHAT and SENGUPTA—Indian Institute of Science, Bangalore, India; JINADASA AND ARULANANTHAN—National Aquatic Resources Research and Development Agency, Colombo, Sri Lanka; FERNANDO, LOZOVATSKY, CONRY, AND LEO—University of Notre Dame, Notre Dame, Indiana; AGRAWAL AND SHARMA—Space Applications Centre, Ahmedabad, India; BAUMGARTNER, FARRAR, MAHADEVAN, ST. LAURANT, AND WELLER—Woods Hole Oceanographic Institution, Woods Hole, Massachusetts; CENTURIONI, HORMANN, JOHNSTON, LANKHORST, LUCAS, MACKINNON, PHAM, PINKEL, RUDNICK, SARKAR, SEND, WATERHOUSE, AND WHALEN—Scripps Institution of Oceanography, La Jolla, California; LEE, RAINVILLE, AND STAFFORD—Applied Physics Laboratory, University of Washington, Seattle, Washington; GORDON—Lamont–Doherty Earth Observatory of Columbia University, Palisades, New York; OMAND—University of Rhode Island, Narragansett, Rhode Island; SIMMONS—University of Alaska Fairbanks, Fairbanks, Alaska; VENAGAPADMOORTHY—Colorado State University, Ft. Collins, Colorado; VENKATESAN—National Institute of Ocean Technology, Chennai, India

**CORRESPONDING AUTHOR:** Hemantha Wijesekera, Naval Research Laboratory, Stennis Space Center, MS 39529

E-mail: hemantha.wijesekera@nrlssc.navy.mil

The abstract for this article can be found in this issue, following the table of contents.

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interactions in the Bay of Bengal. The specific objectives of ASIRI are to

- observe atmospheric (moisture, temperature, winds, and surface fluxes) and upper-ocean (currents, temperature, salinity, and turbulent diffusivity) properties throughout the BoB from diurnal to seasonal time scales;
- examine the role of the freshwater distribution on SST, mixed layer depth, barrier layer strength and evolution, stratification, and currents;
- characterize the coastal boundary current, tides, internal waves, and mixing around Sri Lanka in relation to interbasin exchanges;
- improve quantitative understanding of seasonally varying mesoscale phenomena (e.g., the Sri Lanka dome and transbasin eddies) and their influence on air–sea interaction;
- observe and understand subseasonal to seasonal variability of the atmospheric boundary layer (ABL) and ocean MLs and their feedbacks with basin-scale propagation of the intraseasonal oscillation (ISO; Sengupta et al. 2001) and Madden–Julian oscillation (MJO; Madden and Julian 1971) events.

**FIELD PROGRAM.** The ASIRI initiative includes multiyear field surveys (Tables 1 and 2) integrated with atmosphere–ocean coupled model simulations (Table 3). Ocean field observations span the microscale, $O(1)$ cm to regional scale $O(1,000)$ km, by including short intensive shipboard campaigns with multiyear mooring and drifter deployments (Fig. 1). ASIRI also integrates remote sensing products, air–sea atmospheric flux measurements, and ABL observations.

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**Table 1. ASIRI lead principal investigators (PIs) and institutions concerned with ocean observations in the BoB. (Full institution names can be found in the affiliations.) Observations included temperature $T$, salinity $S$, pressure $P$, currents, SST, SSS, SSH, microstructure, AOP, IOP, fast repetition rate fluorometer (FRRF), and color. Policies of data sharing are described in a sidebar.**

<table>
<thead>
<tr>
<th>Institutions (lead PIs)</th>
<th>Instruments/platforms</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>UW (Lee), NARA</td>
<td>Seagliders</td>
<td>$T$, $S$, $P$, profiles</td>
</tr>
<tr>
<td>SIO (Rudnick)</td>
<td>Spray gliders, profiling floats</td>
<td>$T$, $S$, $P$, profiles</td>
</tr>
<tr>
<td>SIO (Centurioni), NARA</td>
<td>SVP drifters</td>
<td>Surface currents</td>
</tr>
<tr>
<td>IIS (Sengupta), INCOIS (Ravichandran), NIOT (Venkatesan)</td>
<td>Drifters</td>
<td>Surface currents</td>
</tr>
<tr>
<td>SIO (Send), NARA</td>
<td>PIES</td>
<td>SSH, currents</td>
</tr>
<tr>
<td>NARA (Jinadasa), ND, NRL</td>
<td>ADCP, CTD, strings</td>
<td>Currents, $T$, $S$, $P$</td>
</tr>
<tr>
<td>SIO (Mackinnon, OSU (Shroyer))</td>
<td>CTD, UCTD, ADCP</td>
<td>$T$, $S$, $P$, currents</td>
</tr>
<tr>
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<td>CTD, UCTD, XBT, expendable CTD (XCTD), ADCP</td>
<td>$T$, $S$, $P$, currents</td>
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<tr>
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<td>Towed chain</td>
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<td>Microstructure</td>
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<td>NRL (Wijesekera)</td>
<td>ScanFish</td>
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<tr>
<td>WHOI (St. Laurent)</td>
<td>Slocum glider</td>
<td>Microstructure</td>
</tr>
<tr>
<td>IIS (Sengupta)</td>
<td>Microprofiler</td>
<td>Microstructure</td>
</tr>
<tr>
<td>ND (Lozovatsky)</td>
<td>VMP</td>
<td>Microstructure</td>
</tr>
<tr>
<td>OSU (Moum, Shroyer, Nash)</td>
<td>Chi pods</td>
<td>Microstructure</td>
</tr>
<tr>
<td>NARA (Jinadasa), ND (Lozovatsky)</td>
<td>VMP</td>
<td>Microstructure</td>
</tr>
<tr>
<td>UW (D’Asaro)</td>
<td>Lagrangian floats</td>
<td>Mixed layer $T$, $S$, $P$</td>
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<td>WHOI (Mahadevan)</td>
<td>Fluorometer, hyperspectral radiometer</td>
<td>AOP, IOP, FRRF</td>
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<td>IIS (Sengupta), INCOIS (Ravichandran), NIOT (Venkatesan)</td>
<td>Fluorometer, hyperspectral, radiometer</td>
<td>AOP, IOP, FRRF</td>
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<td>SST, SSH, SSS, color</td>
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<td>NRL (Wijesekera)</td>
<td>Subsurface moorings</td>
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</tr>
<tr>
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<td>Surface mooring</td>
<td>$T$, $S$, $P$, currents</td>
</tr>
<tr>
<td>LDEO (Gordon)</td>
<td>Hydrographic data</td>
<td>$T$, $S$, $P$, currents</td>
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</tbody>
</table>
### Table 2. ASIRI lead PIs and institutions concerned with atmospheric boundary layer observations in the BoB.

<table>
<thead>
<tr>
<th>Institutions (lead PIs)</th>
<th>Instruments/platforms</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHOI (Weller, Farr)</td>
<td>Surface mooring</td>
<td>Heat, momentum fluxes</td>
</tr>
<tr>
<td>ND (Fernando), ARL, NARA</td>
<td>Microwave radiometers, lidars, radiosondes, ceilometers, flux towers, weather stations, sky cameras</td>
<td>Heat, moisture, and momentum fluxes; cloud heights and intensity; wind, air temperature, humidity, turbulence</td>
</tr>
<tr>
<td>NARA (Jinadasa), NRL (Wijesekera)</td>
<td>Weather station</td>
<td>Standard meteorological measurements</td>
</tr>
<tr>
<td>IIS (Sengupta), INCOIS (Ravichandran), NIOT (Venkatesan)</td>
<td>Radiometers, radiosonde, aethalometer, dust track</td>
<td>Heat and momentum fluxes</td>
</tr>
</tbody>
</table>

**Ocean measurements.** Long-term time series are being collected through multiyear mooring deployments, which include a six-element water column subsurface array distributed between 5° and 8°N and 85.5° and 88.5°E in the southern BoB and a solo deployment near 18°N, 89°E in the northern BoB (Figs. 1, 2a,b). The NRL-led southern array was deployed in December 2013 and was successfully recovered in August 2015. These subsurface moorings provide currents in the upper 600 m from acoustic Doppler currents profilers (ADCPs), supplemented by hydrographic data and turbulent dissipation rates at selected depths using Sea-Bird MicroCats and Chi pods (Moum and Nash 2009), respectively. The shallowest measured depth of currents is 8 m below the surface. The Woods Hole Oceanographic Institution (WHOI)-OMM 18°N mooring deployment spans December 2014–January 2016 and provides concurrent measurements of surface meteorology; air–sea fluxes of heat, freshwater, and momentum; and upper-ocean temperature, salinity, velocity, and turbulent mixing. Three nearby Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA; McPhaden et al. 2009) moorings maintained by the National Oceanic and Atmospheric Administration (NOAA) and five moorings maintained by the National Institute of Ocean Technology (Chennai, India) augment the specialized instrument deployments (Fig. 1).

The Lagrangian Drifter Laboratory at the Scripps Institution of Oceanography (SIO) partnered with NARA to deploy three Surface Velocity Program (SVP) drifters drogued at 15-m depth (Niiler 2001) every month off Sri Lanka between May 2013 and September 2015, primarily using the research vessel (R/V) *Samudrika*. A total of 64 satellite-tracked SVP drifters were deployed between 2013 and 2014 (Figs. 1, 3a). A thermistor on all SVP drifters measured the SST every 15 min, with the data being transmitted on a roughly 1–2-h basis. In addition to these regular deployments, during the 2015 field campaign a one-time deployment of 36 salinity SVP drifters was used.

![Fig. 1. Map illustrating BoB multiyear observational program. The color image represents the bathymetry and the white lines are the exclusive economic zones (EEZs). Thin yellow and thin blue lines are the R/V Roger Revelle tracks for legs 1, 2, and 3 in Nov–Dec 2013 and in Jun–Jul 2014. Thick white lines and purple line denote Seaglider and Spray Glider tracks, respectively. The yellow rectangle near 19°N, 89°E is the region where a process study was conducted in Aug–Sep 2014 from Sagar Nidhi. The black diamond, orange triangles, green bullets, and red triangles denote locations of WHOI–OMM, NRL, NIOT, and RAMA moorings, respectively. Two red circles are locations of ADCP moorings. PIEs are marked by yellow stars. The weather stations and atmospheric measurement towers in Sri Lanka are marked by blue squares. The purple star denotes turbulent glider observations. Thin gray lines are surface drifter tracks.](image-url)
to map the sea surface salinity (SSS) and SST distributions and variability in the northern BoB at higher temporal and spatial resolution.

Partnered with NARA scientists, volume transports of boundary currents around Sri Lanka are being measured using pressure sensor–equipped inverted echo sounders (PIESs), which record seafloor pressure and acoustic travel time vertically through the entire water column. Two PIESs were deployed on the path of the EICC along 8°N (Fig. 1) during November 2014 from the R/V Samudrika, and another two PIESs were deployed along the 80.4°E off southern Sri Lanka in December 2015 for a duration of deployment of up to 4 years with data subsets transmitted through acoustic modems; all data will be retrieved after recovery of the instruments. The data can be projected onto vertical modes of variability in the boundary current and together with satellite altimetry will constrain the boundary current variability with improved understanding of the vertical structure. The first year of PIESs data was retrieved via acoustic telemetry from the 8°N section in November 2015.

On the basin scale, six University of Washington Seagliders, deployed in collaboration with NARA from the R/V Samudrika and chartered vessels, have sampled large-scale gradients and mesoscale variability over the upper 1,000 m. The glider measurements focus on the annual cycle of the lateral and vertical structure of water mass variability and mixing (Fig. 4). Two Seaglider survey lines have been maintained since 2013 in the southern BoB; one along 8°N between east of Sri Lanka and 90°E, and the other along 81°E between south of Sri Lanka and 2°N (Figs. 1, 4). Two

Table 3. ASIRI lead PIs and institutions focused on BoB modeling.

<table>
<thead>
<tr>
<th>Institutions (lead PIs)</th>
<th>Model</th>
</tr>
</thead>
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<tr>
<td>NRL (Jensen)</td>
<td>Ocean–atmosphere coupled</td>
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<tr>
<td>UA (Simmons)</td>
<td>Regional scale</td>
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<tr>
<td>WHOI (Mahadevan)</td>
<td>Bio-optical</td>
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<tr>
<td>UMassD (Tandon)</td>
<td>Submesoscale</td>
</tr>
<tr>
<td>SIO and UCSD (Sarkar)</td>
<td>Small scale</td>
</tr>
<tr>
<td>CSU (Venayagamoorthy)</td>
<td>Small scale</td>
</tr>
</tbody>
</table>

Fig. 2. (a) WHOI–OMM surface mooring from the Sagar Nidhi, (b) deployment of NRL subsurface moorings from the Roger Revelle, (c) deploying UCTD, (d) deploying a WW profiling package with multiple sensors, and (e) deploying radiosonde from the Sagar Nidhi.
Spray underwater gliders have been deployed to run a north–south line along 88°E between 9° and 17°N (Fig. 1). Three additional Sounding Oceanographic Lagrangian Observer-II (SOLO-II) profiling floats were deployed in the north-central BoB to supplement the international Argo campaign and to provide a complementary perspective to long-range glider transits.

Multiple shipboard campaigns provide large-scale rapid surveys, intensive feature tracking, and small-scale process studies using the R/V *Roger Revelle* and R/V *Sagar Nidhi* (Fig. 1; Table 1). Measurements were expanded to resolve near-surface properties through inclusion of two additional high-frequency ADCPs and a bow-mounted T–S chain. Rapid ship-based

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Fig. 3. (a) Tracks of 64 SVP drifters deployed during 2013/14. (b) Tracks of eight drifters deployed east of Sri Lanka and in southern BoB between 24 Oct and 23 Dec 2013 showing the EICC. (c) Drifter tracks (A–H) and speeds (color shading) in m s⁻¹. The arrows indicate velocity vectors at 21.5-m depth along the *Roger Revelle* track on 23–24 Dec 2013 from 150-kHz ADCP. (right) Enlarged view of drifter tracks and speeds around Sri Lanka.
profiling was accomplished using multiple platforms, including Oceanscience’s underway conductivity–temperature–depth profiler (UCTD); a ScanFish, towed, undulating profiler; and the SIO’s FastCTD system. Turbulent mixing rates, inherent and apparent optical properties (IOP/AOP), nutrients, and CTDs were collected from the ship-based vertical profilers (Table 1). Coastal and western boundary surveys around Sri Lanka were carried out using the R/V Samudrika, gliders, drifters, and PIES.

Short-term autonomous assets, including mixed layer floats, upper-ocean profiling floats, near-surface spar
buoys, profiling wirewalkers (WWs), and microstructure gliders, provided an uncontaminated view of the near-surface and shallow mixed layer characteristics of the BoB. For example, drifting wirewalker (Fig. 2d) arrays (3–4 units) formed the reference for high-resolution ship sampling during the 2013 and 2014 cruises on the R/V Roger Revelle. Wirewalkers use energy from the surface wavefield to drive a vehicle vertically along a wire (Pinkel et al. 2011; Rainville and Pinkel 2001). The resulting rapid profiling down to 150 (2013) and
100 m (2014) provided one profile every 15 and 10 min, respectively. Wirewalker sensors included CTD, current, chlorophyll fluorescence, colored dissolved organic matter (CDOM), optical backscatter, dissolved oxygen, hyperspectral irradiance, and temperature microstructure.

**Satellite observations.** Satellite products are used to examine BoB submesoscale to regional scale, and diurnal to seasonal variability include merged products of sea surface height anomaly (SSHA; [www.aviso.altimetry.fr/en/data.html](http://www.aviso.altimetry.fr/en/data.html); e.g., Kurien et al. 2010; Cheng et al. 2013), SST, and outgoing longwave radiation (OLR) from geostationary platforms, high-resolution (1 km) Group for High-Resolution Sea Surface Temperature (GHRSSST) and NOAA Advanced Very High Resolution Radiometer (AVHRR), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Ocean Color Monitor (OCM), and Moderate Resolution Imaging Spectroradiometer (MODIS) products. Synthetic aperture radar (SAR) missions, **Radar Imaging Satellite (RISAT), Radarsat-2** ([www.asc-csa.gc.ca/eng/satellites/radarsat2/](http://www.asc-csa.gc.ca/eng/satellites/radarsat2/)), and **TerraSAR-X** are being used to examine finescale fluctuations and internal waves. The SSS products from **Aquarius** (launched in 2011 and ended on 8 June 2015) and Soil Moisture Ocean Salinity (SMOS; e.g., Lagerloef et al. 2010) will be used to understand the seasonal variability of salinity at large scales.

**ABL measurements.** ASIRI-RAWI is targeting atmospheric phenomena with oscillations on the order of 30–90 days (e.g., MJO) and shorter, including quasibiweekly oscillations (QBO) as well as synoptic and mesoscale phenomena down to turbulence in the surface layer. To this end, a suite of meteorological instruments was deployed from February through March 2015 in the Seychelles (4.68°S, 55.53°E), Sri Lanka (6.98°N, 79.87°E), and Singapore (1.3°N, 103.77°E) to capture the propagation of such disturbances through the BoB ([http://ceees.nd.edu/research-facilities/projects/asiri-rawi](http://ceees.nd.edu/research-facilities/projects/asiri-rawi)). Collectively, various sites acquired vertical profiles of temperature, humidity, wind speed, wind direction, vertical velocity, cloud cover, precipitation, and radiation as well as

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**Fig. 6.** Winter monsoon currents in the southern BoB. (a) **R/V Roger Revelle** tracks during leg 3. T18 is the ship transect on 18 Dec 2013, and T24 is the ship transect on 23–24 Dec. The green dots represent the mooring and CTD locations. (b) Wind vectors based on hourly averages along the ship track. Blue and red arrows denote winds along T18 and T24, respectively. (c) Upper 175-m depth-averaged ADCP current vectors along the ship track. Velocity along (d),(e) T18 and (f),(g) T24. Sections of (d),(f) zonal velocity $U$ and (e),(g) meridional velocity $V$. Velocity contours of $-1$ and $-0.5$ m s$^{-1}$ are marked by black lines, and contours of $+0.5$ m s$^{-1}$ are marked by white lines.
The data collected in international waters of the Bay of Bengal as part of ASIRI–EBOB and ASIRI–OMM will be available to the research community worldwide. The data collected by ONR and NRL investigators are embargoed for a period of 3 years to allow quality assurance (QA)/quality control (QC) of data and completion of publications. Outputs of model simulations conducted by the NRL will also be available at the U.S. Navy Department of Defense (DoD) Supercomputing Resource Center. The above data sharing policies do not apply to those data collected by the international partners, who will follow their internal protocols and ASIRI–EBOB and ASIRI–OMM agreements. Restrictions apply to data collected in EEZs or inland of partner countries, who have granted access on special terms. The sharing of water column observations within Sri Lanka territorial waters requires written permission from the National Aquatic Resources Research and Development Agency, Sri Lanka. Hosting of the bulk of data on a central database is being considered. For inquiries about data sharing contact the first author.

Fig. 7. Summer monsoon currents in the southern BoB. (a) Wind vectors along the R/V Roger Revelle tracks during the mooring recovery in Aug 2015. (b) Upper 175-m depth-averaged ADCP current vectors along the ship track. Sections of (c) zonal velocity $U$ and (d) meridional velocity $V$ along the outbound track and (e) $U$ and (f) $V$ along the inbound track.

DATA SHARING

The data collected in international waters of the Bay of Bengal as part of ASIRI–EBOB and ASIRI–OMM will be available to the research community worldwide. The data collected by ONR and NRL investigators are embargoed for a period of 3 years to allow quality assurance (QA)/quality control (QC) of data and completion of publications. Outputs of model simulations conducted by the NRL will also be available at the U.S. Navy Department of Defense (DoD) Supercomputing Resource Center. The above data sharing policies do not apply to those data collected by the international partners, who will follow their internal protocols and ASIRI–EBOB and ASIRI–OMM agreements. Restrictions apply to data collected in EEZs or inland of partner countries, who have granted access on special terms. The sharing of water column observations within Sri Lanka territorial waters requires written permission from the National Aquatic Resources Research and Development Agency, Sri Lanka. Hosting of the bulk of data on a central database is being considered. For inquiries about data sharing contact the first author.
observations, instrumentation, and contributing institutions are given in Table 2.

**Observations and Preliminary Results.** A total of six cruises were successfully conducted in international waters of the BoB using the R/V Roger Revelle in collaboration with the R/V Sagar Nidhi. Five Roger Revelle cruises were carried out from Colombo, Sri Lanka, in November–December 2013, July–August 2014, and August 2015; two Revelle cruises took place out of Chennai, India, in June 2014 and August–September 2015. Three Sagar Nidhi cruises were conducted in November–December 2013, August–September 2014, and August–September 2015. Since January 2013, coastal and boundary current observations around Sri Lanka have been carried out by the R/V Samudrika. A few preliminary results from the integrated observational efforts are summarized below.

**Coastal transports and boundary currents around Sri Lanka.** Circulation and hydrographic structure over the Sri Lankan shelf, slope, and deep ocean (Fig. 1) were examined through collaborations between NARA and U.S. partners (Fig. 5a). Many of these observations are the first of their kind in this region. Sea surface height anomaly [Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO)] indicates that the boundary current across the section east of Sri Lanka is dominated by semiannual variability, while annual variability dominates the section south of Sri Lanka. The 2014 PIES observations confirm a semiannual variability in transport to the east of Sri Lanka. In situ observations include CTD and microstructure measurements that were collected along two offshore transect lines: a zonal transect along 8°N and a meridional transect along 80.4°E (Figs. 5b,c). These hydrographic observations illustrate the differences in stratification around Sri Lanka during April and September. In late April, the mixed layer depth (MLD) along 80.4°E varied between 20 and 30 m. In September, the thermohaline structure off the east coast of Sri Lanka indicated that there was a sharp front over about 10 nautical miles (n mi; 1 n mi = 1.852 km) at ~40 n mi from the coast. The onshore side of the front contained a 10–20-m-thick layer with low-salinity (<33.8 psu) and high-temperature (>28.5°C) water, while its offshore side had a deeper mixed layer with a subsurface (~50 m) salinity maxima. Seaglider hydrographic sections along 8°N indicate rising isohalines near the Sri Lankan coast in February 2014 and a more patchy salinity field in April 2014. In February and March, depth-averaged flows were typically near 0.5 m s⁻¹; the currents were weaker and more variable in April (Fig. 4).

Regular Lagrangian drifter deployments in the coastal waters of Sri Lanka provide information about the lateral structure, flow patterns, and speeds of the boundary current east of southern India and around Sri Lanka (Fig. 3a). During November–December 2013, the EICC (Figs. 3b,c) was confined to a narrow boundary current southeast of India and east of Sri Lanka prior to developing into an approximately 200-km-wide current as it turned to the west, south of Sri Lanka. Shipboard ADCP sections from December 2013 show the subsurface structure in the vicinity of the EICC (Fig. 6). To the east of the EICC,
The 2-km-resolution ocean component of COAMPS, the Navy Coastal Ocean Model (NCOM; Martin 2000), includes tides and interacts with a 6-km resolution modeled atmosphere and a 13-km resolution Simulating Waves Nearshore (SWAN) spectral wave model (Booij et al. 1999). These coupled models exchange fluxes every 6 min. This regional coupled model setup has been validated for several regions around the world (Allard et al. 2012). For the BoB, the regional-scale atmospheric and oceanic states are also in good agreement with observations, which is to be expected since the model assimilates data and uses boundary conditions from the Navy Global Environmental Model and the global Hybrid Coordinate Ocean Model.

COAMPS fields have been compared to both ocean currents and temperature fields near the equator (Jensen et al. 2015) and shipboard meteorological observations (Chen et al. 2015). The simulated near-surface winds, ocean currents, and salinity during the northeast monsoon are shown for December 2013, when the western equatorial Indian Ocean was experiencing westerly winds of an MJO event (Fig. SB1). Spatially varying surface wind fields include the intensification of winds between the gap of India and Sri Lanka and a shadow zone southwest of Sri Lanka. A 24-h forecast of salinity at 60 m on 24 December 2013 shows the advection of low-salinity water along the Sri Lanka east coast and the offshore subsurface intrusion of high-salinity Arabian Sea water, qualitatively similar to the observed fields (Fig. 6). Zonal depth sections of observed and modeled currents along 5.25°N on 23 December 2013 show that the model captures the basic features of the flow, although the strength and locations of currents vary from the observations (Fig. SB2).

**Submesoscale processes modeling.** The ASIRI submesoscale modeling uses high-resolution process study models capable of resolving $O(1–10)$ km lateral density gradients and instabilities, with finer-scale, large-eddy simulations (LESs) focusing on vertical and lateral mixing at open-ocean bores and boundary layer mixing in the presence of barrier layers. Previous observational and modeled data suggest that high-salinity water intrudes into the bay during the southwest monsoon (e.g., Murty et al. 1992). These data show northward flow carried high-salinity water into the BoB during the northeast monsoon as well. These observations are qualitatively consistent with numerical simulations described in the sidebar on the modeling program (Wijesekera et al. 2015).

Snapshots of the SMC entering into the BoB from south-southeast of Sri Lanka in August 2015 (Fig. 7) reveal notable differences between zonal and meridional components of the SMC; the meridional component has a subsurface maximum of about $0.6 \text{ m s}^{-1}$ near 100-m water depth, while the zonal component has a surface maximum of about $0.8 \text{ m s}^{-1}$. CTD casts taken at mooring sites showed
numerical studies (e.g., Mahadevan et al. 2012; D’Asaro et al. 2011; Mahadevan and Tandon 2006) have demonstrated the crucial role of submesoscale instabilities in restratifying the upper ocean in regions with deep [O(100) m] mixed layers. To explore the potential for submesoscale instabilities in monsoon conditions characterized by shallow [O(10) m] mixed layers, a series of submesoscale-resolving simulations have been conducted using the Process Study Ocean Model (PSOM; Mahadevan and Tandon 2006).

For example, a PSOM simulation (Fig. SB3) was initialized with a south–north density gradient inferred from Argo floats near 18°N during August 2013. The horizontal grid resolution is 1 km, and the vertical grid resolution varies from O(1) m at the top to 20 m at the bottom of the domain. The model is forced with daily winds and hourly heat fluxes for August 2013. The precipitation in the model occurs at a rate of 40 mm h\(^{-1}\) for 1.5 h, followed by a gap of 2 days before the next rain event. The forcing is imposed after the mixed layer front goes unstable to ageostrophic baroclinic instabilities (Boccaletti et al. 2007; Fox-Kemper et al. 2008) in 4.8 days (approximately three inertial periods). The rainfall was constrained to a 100-km-wide meridional band, thus enabling the exploration of mechanisms for transport of freshwater in a BoB-like regime. Before the onset of surface forcing, mixed layer instabilities (Boccaletti et al. 2007) generate numerous dipole structures with strongly ageostrophic vorticity filaments characterized by O(1) Rossby numbers (Fig. SB3). The presence of forcing disrupts the dipolelike formation of these features and weakens the vorticity field slightly, though filaments with relative vorticity \(\zeta \sim O(f)\) continue to exist at the frontal edges. This simulation shows submesoscale signatures in shallow, stratified layers, with conditions markedly different from the deep O(100) m wintertime mixed layers characterizing earlier observational and numerical studies (Boccaletti et al. 2007).

Turbulence process modeling. A three-dimensional LES model (Pham et al. 2013) has been used to understand barrier layer dynamics with unprecedented resolution: O(cm) vertical and O(m) horizontal. The unusually small vertical entrainment by wind forcing found in the LES is consistent with ASIRI observations. The sharp lateral gradients that are ubiquitous in the observations admit the possibility of three-dimensional instabilities and turbulence (Arobone and Sarkar 2015) during equilibration. These processes are also being studied using LES with O(m) resolution in the horizontal and vertical.

that a layer of high-salinity water was associated with the northward flow. A similar subsurface water mass structure was discussed by Vinayachandran et al. (2013).

The reversing flow patterns, eddies, and intraseasonal fluctuations are observed in the time–depth sections of velocity from the NRL mooring at 6.5°N, 87°E (Fig. 8). The zonal flow in the upper 200 m was westward during the northeast monsoon (January–March in 2014, 2015) and reversed to eastward during summer monsoon. During summer, the SMC resided between a cyclonic circulation and an anticyclonic eddylike feature to the southeast (e.g., Vinayachandran et al. 1999). Intraseasonal oscillations with periods close to 60 days in the meridional component of velocity are apparent. The mooring observations captured the movement of the SMC/eddy structure, which is also consistent with the AVISO SSH anomalies and drifter tracks (not shown).
Fig. SB3. Evolution in time $t$ of near-surface ($z = -2.3$ m) vorticity and salinity. The winds, heat, and salt fluxes are turned on at $t_f / 2\pi = 3.1$. The filaments with $O(1) \zeta / f$ persist under the influence of surface forcing and rainfall. In spite of the initial freshening due to rainfall, strong mixing results in a significant increase in salinity.
Regional and mesoscale variability: Currents, hydrography, and bio-optics. The BoB interior has distinct regional gradients in hydrographic and bio-optic properties (e.g., Murty et al. 1996; Rao et al. 2011; Vinayachandran et al. 2002). Deployments of two Spray underwater gliders and three SOLO-II profiling floats were undertaken with a goal of observing low SSS layers and the underlying regional-scale thermohaline fields (Fig. 9). Over 1,000 profiles, collected to date, show frequent occurrence of low SSS layers, with greater prevalence in the northern BoB. A float deployed in the northern BoB observed an SSS of less than 28.5 psu with a density of less than 1,018 kg m$^{-3}$ in a layer roughly 20 m thick. Salinity drifters have recorded surface salinity as low as 25 in the northern BoB at 200-km distance from the Ganges’ delta. This low SSS layer was observed in a sequence of a few profiles separated by 5 days. A glider section in the central BoB showed low SSS layers similar in depth though with slightly higher salinity. The preliminary analysis suggests that the SSS along Aquarius tracks and the SSS from SOLO-II floats were comparable to one another, suggesting a path toward better quantification of time–space variability in freshwater lenses in future analysis.

Shipboard surveys also provide a means of assessing the spatial variability in low-salinity lenses. For example, the August–September 2014 Sagar Nidhi survey in northern BoB (Fig. 2c) measured strongly stratified, shallow, salinity-controlled layers that occasionally outcropped at the surface (Fig. 10b). In this data record, subsurface, large lateral gradients in $T$ and $S$ and near-surface stratification are enhanced under fronts.

During the November–December 2013 leg of the Roger Revelle, the large-scale underway CTD mapping was interspersed with regular CTD rosette stations approximately every 40 n mi for a total of 81 rosette...
casts during the cruise. Each cast provided a vertical profile of temperature, salinity, nitrate, dissolved oxygen (DO), chlorophyll fluorescence (Chl-FL), photosynthetically available radiation (PAR), and AOPs and IOPs up to a depth of 220 m (Fig. 11). Nitrate was measured with a Submersible Ultraviolet Nitrate Analyzer (SUNA V2) ultraviolet sensor. ML depths (estimated as the depth where density differs by 0.1 kg m$^{-3}$ from the surface density) ranged between 5 and 30 m, and the euphotic depths ranged between 60 and 104 m. The oxycline and nitracline follow closely with the 1,022 kg m$^{-3}$ isopycnal. Chl-FL shows the presence of a deep chlorophyll maximum (DCM) that roughly tracked the 1,022 kg m$^{-3}$ isopycnal (Fig. 11). The BoB is one of the major oxygen minimum zones of the world, where the suppression of convective overturning by freshwater stratification prevents ventilation of the pycnocline. Here, phytoplankton production within the pycnocline could be an important source of oxygen for heterotrophs in the upper pycnocline.

A comparison of T–S properties derived from Argo and the 2013 shipboard underway CTD data (spatial resolution of a few kilometers) highlights water masses and thermohaline gradients across the basin (Figs. 12, 13). The northern end of the BoB is considerably fresher than the south-central BoB (SSS near 30 psu as compared to 33 psu). During November–December 2013, the lowest-salinity water resides in the northeast corner of the BoB. The warm, high-salinity (>34 psu) Arabian Sea water can be found in the thermocline near 50–70 m and in a high-salinity layer near 120–150 m (Fig. 13). The Argo comparison allows inference of the likely origin of the waters within the observed eddy field, including an intrathermocline eddy (ITE; Fig. 14) and reconstruction of the regional circulation patterns. The geostrophic current relative to 200 m, marking the base of the ITE, showed a maximum current of ~0.25 m s$^{-1}$ at 70–80-m depth. The surface current
was about 50% of the subsurface velocity maximum, so the ITE did have a surface expression in the velocity field, which is unlike the ITE observed in the Sea of Japan (Gordon et al. 2002).

**Finescale fronts, filaments, and internal waves.** Thermal fronts can play a significant role in air–sea interactions, upper-ocean vertical structure, biological productivity, lateral and vertical mixing processes, and modification of cyclone tracks, but these features have received scant attention (Ramachandran et al. 2014). Preliminary analysis shows that the high-resolution (1 km) GHRSSST daily mean product allows for detection of sharp frontal features during cloud-free conditions (Fig. 15). The subsurface details of one example front are captured by the wirewalker array data (Fig. 16). In this example, three profilers were released in a cluster with an initial separation of 3 km, spanning a front, and allowed to drift for ~2 days while the ship traversed short sections with the underway CTD, pole-mounted ADCP, and bow chain. During the drift, the vertical structure above the main pycnocline was dominated by salinity stratification (Figs. 16c,d). The mixed layer deepened by >20 m over roughly 24 h and 5-km drift, coincident with a subsurface temperature maximum of decreasing thickness. Squared vertical shear in the horizontal currents was intensified at the base of the mixed layer and, at times, within the pycnocline (Fig. 16f). The turbulent heat flux based on observations of temperature–variance dissipation rate $\chi$ showed an upward heat flux across the base of the mixed layer of $\sim$5–10 W m$^{-2}$ associated with elevated dissipation and the local subsurface thermal maximum, including increased SST (Fig. 16g). Elevated chlorophyll, centered at ~30 m, was observed in association with the front (Fig. 16e). The measured chlorophyll fluorescence was significantly higher than that observed elsewhere. The pycnocline is characterized by interleaving of density-compensated temperature and salinity features with small vertical scales (<10 m) associated with elevated

**Fig. 11.** (a) Map showing the boundaries of the Bay of Bengal and the country EEZs (dotted). The ship’s track is denoted by the curtain plot, which shows salinity in the upper 220 m (blue is fresh and red is saline). Vertical $Z$ along-track sections of (b) nitrate, (c) dissolved oxygen, and (d) chlorophyll fluorescence plotted along the ship’s trajectory. These were measured on the CTD casts, several of which are missing in leg C because of the passage of a hurricane. Legs A, B, C, and D refer to the sections shown in (a), where A traverses northward, B traverses southward, C traverses eastward, and D traverses southward.

**Fig. 15.** Schematic of the ship’s track showing the measurement of environmental conditions along the track. The ship’s track is denoted by the curtain plot, which shows salinity in the upper 220 m (blue is fresh and red is saline). Vertical $Z$ along-track sections of (b) nitrate, (c) dissolved oxygen, and (d) chlorophyll fluorescence plotted along the ship’s trajectory. These were measured on the CTD casts, several of which are missing in leg C because of the passage of a hurricane. Legs A, B, C, and D refer to the sections shown in (a), where A traverses northward, B traverses southward, C traverses eastward, and D traverses southward.
shear and $\chi$ (Figs. 16f,g). These features were especially notable below regions of elevated chlorophyll feature.

The internal wave climate of the BoB is poorly characterized, apart from relatively sparse measurements of the semidiurnal tides and high-frequency waves obtained over the past several decades (e.g., Wijeratne et al. 2010; Jackson 2007; Antony et al. 1985; Osborne and Burch 1980; Perry and Schimke 1965). ASIRI observations provide new insights into the internal wavefield through the NRL mooring array (Fig. 1), which spanned the path of tidal beams radiating from Andaman–Nicobar Island gaps toward Sri Lanka (e.g., Jackson 2007). Displacement spectra of internal waves at 6.5°N, 87°E were computed from moored temperature records (20-month-long records at 1-min resolution) following Levine et al. (1987). The displacement spectra show diurnal and semidiurnal (M2) tides, several superharmonics of tides, and high-frequency bump at approximately one-fifth of the local buoyancy frequency (Fig. 17). The energy levels at higher-frequency bands are significantly larger than the canonical open-ocean estimates specified in the Garrett–Munk spectral model (Garrett and Munk 1979), suggesting that tidally driven mixing may be a significant factor in the southern BoB.

**Atmospheric boundary layer during non-MJO period.**

The beginning of ASIRI–RAWI campaign coincided with the decaying phase of the MJO signal over the tropics according to the Real-time Multivariate MJO index (Wheeler and Hendon 2004), thus permitting observations of subseasonal non-MJO phenomena. For example, both the Seychelles and Singapore observations contained high-speed (~5 m s$^{-1}$) packets of zonal winds (jets) with wavelengths on the order of ~10,000 km and at ~15-km heights propagating eastward, suggesting their similarity to equatorial Kelvin waves (Wallace and Kousky 1968; Andrews et al. 1987). Their influence propagated to the ground level through quasi-periodic biweekly breakdown of the lower boundary of the zonal jet, possibly by shear (Yamamoto et al. 2003), resulting in periodic ground level wind bursts.

Of particular interest to ASIRI (OMM and EBOB) was the Sri Lanka meteorological site located close to the BoB (Fig. 18a). The time series of meridional and zonal wind profiles are given in Figs. 18b and 18c. Although regular zonal wind oscillations observed at other sites were absent here, the zonal flow in Sri Lanka was also elevated at ~15 km (9 February). The downward descent of this westerly jet, again possibly...
Fig. 13. Potential temperature ($\theta$, °C) vs salinity (S) for the (left) 2013 Argo profiles within the Bay of Bengal and for the (right) ASIRI 2013 CTD station and underway data: blue dots are the ASIRI data, and black dots are the Argo (same as shown in the left). The low-salinity surface water overlies significant saltier thermocline water. Box A locates a distinct salinity maximum commonly found in the central Bay of Bengal within the 50- to 70-m depth interval drawn from the Arabian Sea. Box B denotes a salinity maximum in the 120–150-m depth interval that is occasionally observed. Box C is low-salinity, upper-thermocline water found within the northern mesoscale survey of ASIRI leg 1. The intrathermocline eddy observed during ASIRI cruise 2 (see Fig. SB2) falls on the low-salinity extreme of the thermocline $\theta$–S scatter. The Argo profiles observe similar $\theta$–S water in the eastern BoB.

Fig. 14. (left) The R/V Roger Revelle leg-2 cruise track. The location of the ITE is marked by the red circle. (right) Salinity (color image) and overlaid isopycnal contours show the ITE.
Fig. 15. (a) Thermal fronts can be seen in the northern BoB from a composite satellite SST image and (b) time series of near-surface temperature at four different depths from a buoy at 18°N, 89.5°E. Horizontal SST gradient magnitude (°C km$^{-1}$) for 15 Jan 2013. The estimated temperature gradients based on (c) 1-km resolution and (d) 10-km resolution.

initiated by shear at the lower boundary, occurred rapidly until ~5-km (on 11 February) height, prompted by weakly stable atmospheric conditions prone to shear instabilities (i.e., low gradient Richardson number $R_i_g$). A very stable layer centered around 4 km with maximum $R_i_g \sim 10–15$ (Fig. 18f) impeded the descent, though downward mixing may have continued across the stable layer at a slower rate. By 15 February, maximum $R_i_g$ decreased to ~4, approaching $R_i_g \sim 1$ at the edges of the stable shear layer. Note that the low-resolution radiosonde measurements, in this case of resolution ~25 m, could overestimate the $R_i_g$, as shown by De Silva et al. (1999). The condition of $R_i_g = 1$ corresponds to the maximum rate of stratified turbulent mixing (Strang and Fernando 2001) and hence could transport significant amounts of dry air from aloft toward the surface. This air mixed with existing surface moist air [70%–90% relative humidity (RH)], thus reducing the ground level RH, followed by a temperature drop due to evaporative cooling (cf. 15–17 February in Figs. 18d,e). Rain events (9, 10, 11, and 13 February), local urbanization, and advection of moist air by the near-surface northwesterly flow over the ocean appear to have contributed to the high RH prior to this event.

The drop of surface temperature impeded convective activity, as evident from the reduced heat flux and velocity variances (Fig. 18e) as well as the height of the capping inversion (ceilometer). Reduced moisture led to the suppression of rainfall until 25 February, whence the surface moisture has increased to the previous levels and the upper-level moisture has increased substantially to resuscitate rainfall activity. The same patterns for RH and temperature were recorded by the instrumented buoy at 8°N, 90°E.
in the BoB, within the same latitudinal band as the Sri Lanka site, which is a part of the RAMA program (McPhaden et al. 2009). This suggests that the vertical transport phenomena observed in Sri Lanka may also be occurring in the BoB, leading to the modulations of near-surface heat and moisture fluxes, thus affecting the air–sea exchange processes. These results point to the significant role that multiscale atmospheric processes, from regional-scale upper-atmospheric flows to entrainment across stratified layers to mixing in the ABL, play in air–sea interactions of the BoB.

**SUMMARY AND CONCLUDING REMARKS.**

ASIRI, a 5-yr (2013–17) research effort of the United States, India, and Sri Lanka is aimed at understanding and quantifying coupled atmosphere–ocean dynamics relevant to the Indian Ocean monsoons. The program has already generated an unprecedented ocean and atmospheric dataset covering multiple space–time processes and model simulations for the BoB. ASIRI has combined multiple observational assets, including multimonth shipboard surveys in three different years, long-term mooring, drifter, float, and glider deployments, and short-term deployments of a variety of autonomous assets (gliders, drifters, floats, and wirewalkers) in order to resolve upper-ocean structure, circulation, and air–sea interactions at spatial scales ranging from basinwide to the microscale.

Preliminary analyses have resolved the salinity and temperature gradients across BoB at resolution down to O(1) km, offering high-resolution detail of submesoscale to mesoscale features. Mesoscale features of interest include the intrathermocline eddies and the seasonally forming cyclonic eddy, the “Sri Lanka dome,” as previously reported by several investigators (e.g., Vinayachandran et al. 1999, 2013). The EICC and its northward-flowing offshore counterpart have been resolved at high resolution, and...
Fig. 17. Normalized displacement spectra at 6.5°N, 87°E. Six spectral estimates based on 20-month-long records at 80-, 90-, 95-, 105-, 110-, and 125-m depth levels are shown; \( f, d, M_2, \) and \( N \) are inertial frequency, diurnal frequency, semidiurnal frequency, and local buoyancy frequency in cycles per hour (cph). The sampling rate of temperature was 60 cph. The displacement spectrum was normalized by multiplying by the local buoyancy frequency (e.g., Levine et al. 1987). GM79 denotes the Garrett–Munk spectral level corresponding to the local inertial frequency (Garrett and Munk 1979).

the combination of these observations with model simulations provides a means of better defining the contribution of such features to the BoB heat and salt balances. Numerical simulations have shown submesoscale signatures of the shallow, stratified layers in the BoB are markedly different than those of deep \( O(100) \) m wintertime mixed layers, confirming earlier observational and numerical studies. Sharp frontal features are pronounced in the northern BoB, where shallow, salinity-controlled mixed layers result from high river runoff and heavy rainfall. Here, lateral stirring processes and vertical mixing near fronts may determine water mass modification. In the southern BoB, energetic internal waves, which were observed along an internal wave beam extending from the Andaman–Nicobar Island gaps, have potential energy levels one order of magnitude larger than those of the open ocean, suggesting that high-frequency internal waves may play an important role in mixing in some regions.

The ABL observations during the decaying phase of the MJO signal permitted observations of subseasonal, non-MJO phenomena, pointing to the significant role that multiscale atmospheric processes play in air–sea interactions in the BoB. An integrated analysis of satellite observations, numerical simulations, and in situ data has already begun and is expected to shed light on how regional-scale oceanic and atmospheric processes control the ABL and upper-ocean ML processes and their interactions, which in turn provide strong feedback on larger-scale processes, including monsoons and their breaks. Processes in the BoB have the potential to have strong effects on regional and global climate patterns, including modifying the atmospheric circulation, heat and salt exchange in the Indian Ocean, and altering of the monsoon and rain patterns.

Ongoing analyses of these atmospheric and oceanic datasets gathered in 2013–17 will allow a greater understanding of upper-ocean circulation and thermodynamics of the northern Indian Ocean and its coupling to the atmospheric circulation including monsoons.

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**MARINE MAMMAL OBSERVATIONS**

A cetacean sighting survey was conducted by an international team of eight observers during the basinwide November 2013 cruise to characterize community composition and the distribution of cetaceans with respect to mesoscale oceanographic features. Cetacean sighting data were collected using binoculars and the naked eye, with the standard marine mammal survey methodology (e.g., Alling et al. 1991). A 1,669-km trackline was surveyed in Beaufort 5 or less sea conditions, and 52 sightings of 12 different species were recorded, including spinner dolphin, striped dolphin, false killer whale, pantropical spotted dolphin, bottlenose dolphin, Risso’s dolphin, common dolphin, sperm whale, pygmy killer whale, pygmy/dwarf sperm whale, blue whale, and killer whale. Sightings were mostly concentrated in the southern BoB, with few cetaceans encountered in the central and northern bay. However, sighting conditions were better in the southern bay when compared to the central and northern bay, so it is unclear if the observed differences in sighting rates between the northern and southern BoB were real. Integrating additional sighting data with concurrent oceanographic observations in this region will help elucidate how cetacean occurrence and distribution are influenced by the monsoons.
Fig. 18. (a) Measurement site in Colombo, Sri Lanka; height–time plots of (b) meridional wind, (c) zonal wind, and (d) relative humidity from the sounding station at the Sri Lanka site. (e) Daily averaged values of RH, air temperature ($T_{\text{air}}$), rainfall rate ($\text{Rain}$), and streamwise, crosswise, and vertical velocity variances $\sigma^2(u)$, $\sigma^2(v)$, $\sigma^2(w)$ measured at the flux tower in Sri Lanka. (f) Vertical profiles of bin-averaged gradient Richardson number in two different representative soundings.

Research Laboratory project, Effects of Bay of Bengal Freshwater Flux on Indian Ocean Monsoon (EBOB). ASIRI–RAWI was funded under the NASCar DRI of the ONR. The Indian component of the program, Ocean Mixing and Monsoons (OMM), was supported by the Ministry of Earth Sciences of India. Some of the drifters deployed during ASIRI were funded by NOAA Grant NA10OAR4320156: “The Global Drifter Program.”
REFERENCES


Martin, P. J., 2000: Description of the Navy Coastal Ocean Model version 1.0. Naval Research Laboratory Rep. NRL/FR/7322/00/9962, 45 pp. [Available from Naval Research Laboratory, Code 7322, Bldg. 1009, Stennis Space Center, MS 39529-5004.]


ACRIDICON–CHUVA CAMPAIGN

Studying Tropical Deep Convective Clouds and Precipitation over Amazonia Using the New German Research Aircraft HALO


Comprehensive in situ and remote sensing observations of deep convective clouds using the new German research jet aircraft HALO have been performed over Amazonia to study the influence of anthropogenic aerosols on the cloud life cycle and precipitation formation processes.

Tropical deep convective clouds profoundly influence the atmospheric energy budget and hydrological cycles and often cause severe weather events (gusts, hail, squall lines, lightning, thunderstorms, flooding). They transfer major parts of the surface solar heating to the atmosphere by releasing latent heat during thermodynamic phase transitions (condensation, freezing); on the other hand, deep convective clouds consume heat energy by melting and evaporation. These energy transfers are realized along various thermodynamic pathways, depending on the availability and the properties of cloud condensation nuclei (CCN) and ice nuclei (IN) (Rosenfeld et al. 2008; Tao et al. 2012) and on thermodynamic conditions (atmospheric gases), which impact the vertical development, microphysical properties, cloud-top height, and electrification of deep convective clouds (Wang and Prinn 2000; Williams et al. 2002; Kolb et al. 2010; Li et al. 2011; Albrecht et al. 2011; Morrison and Grabowski 2013; Fan et al. 2013).

To understand the life cycle of deep convective clouds, their temporal evolution from the cloud base through the mixed-phase level ➤
all the way up to the anvil needs to be observed (Rosenfeld et al. 2008; Pöschl et al. 2009; Rosenfeld et al. 2014). In addition, the complex interactions between cloud, precipitation, aerosol particles, and trace gases depend on dynamic conditions such as the vertical wind shear (Khain et al. 2008, 2009; Fan et al. 2009; Albrecht et al. 2011; Fan et al. 2012; Lebo and Morrison 2014).

The realistic description of precipitation formation in tropical deep convective clouds and the consequences for the hydrological cycle still entail many open issues (Rosenfeld 1999; Machado et al. 2014). In this regard, the impact of changes in land use (deforestation of pristine tropical forest turned into pasture sites mainly for agricultural purposes) is debated, which is a major issue in particular in the tropical rain forests of Amazonia (Durieux et al. 2003; Negri et al. 2004; Fisch et al. 2004; Wang et al. 2010; Albrecht et al. 2011). For example, it is known that the sensible heat flux is higher over pasture than forest (Shukla et al. 1990). Furthermore, Cutrim et al. (1995) showed an increase in cloud cover over deforested areas, and Neves and Fisch (2015) have detected that the deforested areas exhibit a deeper boundary layer than pristine tropical forest regions.

To study these open problems related to tropical deep convective clouds, the combined ACRIDICON–CHUVA campaign was performed. ACRIDICON stands for "Aerosol, Cloud, Precipitation, and Radiation Interactions and Dynamics of Convective Cloud Systems"; CHUVA is the acronym for "Cloud Processes of the Main Precipitation Systems in Brazil:..."
A Contribution to Cloud Resolving Modeling and to the GPM (Global Precipitation Measurement)." A major objective was to quantify the influence of aerosol particles and trace gases (natural and anthropogenic) on cloud evolution and precipitation formation. Furthermore, the cloud thermodynamic, dynamic, and radiative effects were investigated. This involved observations of 1) the clouds' life cycle (including the vertical evolution of cloud properties), 2) the cloud processing of aerosol particles and trace gases (inflow at cloud base and outflow at greater heights out of the anvil), 3) the validity of satellite and radar cloud products, 4) the vertical transport and mixing of trace gases and aerosol particles by deep convective clouds, and 5) the effects of deforestation and biomass burning on cloud evolution.

The ACRIDICON–CHUVA field observations took place in Amazonia. The campaign was centered on the environment of Manaus, a city of two million people. Manaus is an isolated urban area in the central Amazon basin situated at the confluence of the two major tributaries of the Amazon River. Outside this industrial city there is mostly natural forest for over 1,000–2,000 km in every direction. This makes it possible to study the impact of local pollution on cloud evolution by taking measurements upwind and downwind of the city. ACRIDICON–CHUVA was intentionally planned to take place at a time of year (September–October) when the nonlinear interactions between modified cloud microphysics (by higher concentrations of CCN) and thermodynamics (by land cover contrasts) were amplified. It is during the transition between dry to wet season (September–October) that the gradual large-scale advection of humidity in the troposphere increases the conditional thermodynamical instability, while biomass burning peaks just before first rainfalls. This allows the separation of the individual effects on deep convection.

The German High Altitude and Long Range Research Aircraft (HALO) and a suite of ground-based instruments were deployed during ACRIDICON–CHUVA. HALO (see www.halo.dlr.de/) is an ultra-long-range business jet G550 (manufactured by Gulfstream); it is of similar type as the U.S. High-Performance Instrumented Airborne Platform for Environmental Research (HIAPER) (Laursen et al. 2006). HALO, with its high ceiling altitude (up to 15 km) and long endurance (up to 8 h), is capable of collecting airborne in situ and remote sensing measurements of cloud microphysical and radiative properties, aerosol characteristics, and chemical tracer compounds in and around tropical deep convective clouds, which are needed to study the open scientific issues discussed above. Serious difficulties in obtaining such measurements during previous campaigns include icing of aircraft during cloud penetrations, limited ceiling to reach the top of deep convective clouds, and insufficient endurance to study the cloud life cycle, among others. HALO provides unique opportunities to overcome these issues, although aircraft icing still remains a problem.

The ACRIDICON–CHUVA campaign was performed in cooperation with the second intensive operating period (IOP2) of the Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5) experiment (Martin et al. 2016), which collected data over a 2-yr period (2014/15). The GoAmazon2014/5 campaign sought to quantify and understand how aerosol and cloud life cycles in a particular background (relatively clean) in the tropics are influenced by pollutant outflow from a large tropical city. The project addressed the susceptibility of cloud–aerosol–precipitation interactions to present-day and future pollution in the tropics. As part of GoAmazon2014/5, there were six ground stations in and around Manaus as well as coordinated flights of HALO with a Gulfstream-1 (G1) aircraft. The G1, compared to HALO, flew more slowly and at lower altitudes. Coordinated flights of the HALO and G1 aircraft took place during IOP2 to provide simultaneous in situ measurements at different altitudes in and around Manaus. In one set of flights, the two aircraft operated in formation so that they could intercompare and cross-calibrate instrumentation. In another set of flights, the G1 flew at lower altitudes while HALO collected data at higher altitudes so that a simultaneous profile of cloud-related properties below, in, and above clouds was measured. Neither aircraft operating alone could have achieved these observations.

Only few previous aircraft missions had been specifically devoted to deep convective clouds in Amazonia. The first important effort was made during the Tropical Rainfall Measuring Mission (TRMM)–Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) campaign. It focused on the dynamical, microphysical, electrical, and diabatic heating characteristics of tropical convection in the Amazon region. The National Aeronautics and Space Administration (NASA) ER-2 and the Citation II from the University of North Dakota collected cloud data in January–February 1999. The main goal was to validate TRMM observations and retrievals; no special attention was paid to the contrast between polluted and pristine cloud conditions. Results
have been published by, for example, Heymsfield et al. (2002), Stith et al. (2002), and Anderson et al. (2005). Basically, the results from the TRMM–LBA campaign presented the first description of cloud microphysical properties in Amazonia during the wet season. The LBA–SMOCC (LBA–Smoke, Aerosols, Clouds, Rainfall, and Climate) campaign was held in the Amazon region from September to November in 2002. Two Brazilian airplanes were used, from Instituto Nacional de Pesquisas Espaciais (INPE) and Ceará Federal University, both limited to 4-km ceiling altitude. The aircraft from INPE carried aerosol measuring instruments; the second aircraft was equipped with cloud microphysical probes. From the data obtained, Andreae et al. (2004) classified precipitation regimes as function of aerosol loading. They concluded that smoke from forest fires reduced cloud droplet size and delayed the onset of precipitation. The aerosol–cloud–precipitation component of ACRIDICON–CHUVA was conceived as a direct follow-on to the LBA–SMOCC campaign, which had been limited in altitude, range, and instrumentation. In 2004 the Tropical Convection and Its impact on the Troposphere and Lower Stratosphere (TROCCINOX) campaign was carried out over the tropical area around Bauru. It focused on influences of convective clouds on the transformation and transport of chemical trace gas species, on new particle formation, and on lightning (see special issue on TROCCINOX in Atmos. Chem. Phys. at www.atmos-chem-phys.net/special_issue82.html). Previous campaigns with emphasis on aerosol particle properties in the Amazon region were reviewed by Martin et al. (2010). In 2014, the South American Biomass Burning Analysis (SAMBBA) campaign took place in Amazonia. Its main goal was to evaluate the chemical properties of fire emissions in Amazonia.

The focus in the present paper is to introduce the specific processes of deep convective clouds in Amazonia (see next section), to elaborate the research topics addressed by the ACRIDICON–CHUVA campaign (see “Research topics and resulting flight patterns” section), to introduce HALO and its instrumentation (see “Instrumentation of HALO” section), to provide an overview of the conducted research flights (see “HALO flights” section), to characterize the general meteorological and pollution conditions during the campaign (see “General meteorological and pollution conditions” section), and finally to show exemplary results of the observations analyzed so far (see “Exemplary results” section). The paper is meant as a reference for a series of future detailed scientific publications resulting from the ACRIDICON–CHUVA campaign.

**SPECIFICS IN AMAZONIA. Deep convective clouds during the dry season.** To illustrate the processes taking place in tropical deep convective clouds in Amazonia during the dry season (May–August), Fig. 1 shows a conceptual diagram of the effects of increased CCN and IN concentrations. Convective updraft is primarily controlled by the latent and sensible heat of the surface and atmosphere (Silva Dias et al. 2002; Williams et al. 2002). During the transition from the dry to wet season (September–October), sensible heating over deforested areas is increased, lifting cloud base heights and creating conditional instability. The enhanced cloud base updrafts also increase cloud base supersaturation and cloud droplet concentrations (Reutter et al. 2009; Chang et al. 2015; Zheng and Rosenfeld 2015). In the same season, biomass burning increases CCN concentrations and consequently the number
of nucleated cloud droplets with reduced sizes (Rosenfeld and Lensky 1998; Andreae et al. 2004). The smaller cloud droplet size slows the collision–coalescence and moves the rain initiation to greater (cooler) heights, leading to more supercooled liquid water (SLW) in the mixed–phase region. This enhances the production of ice hydrometeors in higher (colder) altitudes, increases latent heating to higher levels, strengthens updraft, and enhances electrification and lightning (Rosenfeld et al. 2008). More ice in greater altitudes of the clouds will also extend the anvils and moisten the upper troposphere. Indeed, Durieux et al. (2003) demonstrated that during the wet season convective clouds have higher cloud tops over deforested regions, and during the dry season deforested areas have more low-level clouds than forested regions. Also, Gonçalves et al. (2015) show large precipitation in Manaus, during the dry to wet season, when the environment is more polluted and the atmosphere is unstable.

Ice nuclei concentrations are at least five orders of magnitude smaller than CCN concentrations. At the lower bounds of supersaturation $S$ that particles typically encounter during the cloud formation process (about 0.1%–0.2%; Krüger et al. (2014)), CCN concentrations are usually in the range between $100$ and $1,000 \text{ cm}^{-3}$ (Paramonov et al. 2015). The CCN concentrations depend strongly on the total aerosol particle number concentration and make up about 10% of the submicrometer particles at $S = 0.1\%$. For higher supersaturations (e.g., $S = 0.1\%$) and large fractions of accumulation mode particles, the CCN fraction can easily amount to 60% of the total particle concentration (Paramonov et al. 2015). In contrast, IN concentrations typically range between 1 and $10 \text{ L}^{-1}$ at a temperature of $-20^\circ \text{C}$ and decrease with increasing temperature (DeMott et al. 2010). There is only one campaign in the Amazon region for which both CCN and IN measurements exist [Amazonian Aerosol Characterization Experiment (AMAZE-08)]; the CCN and IN concentrations were 41–90 $\text{ cm}^{-3}$ for $S = 0.1\%$–0.2% (Günthe et al. 2009) and 0.5–2 $\text{ L}^{-1}$ for a temperature of $-20^\circ \text{C}$ (DeMott et al. 2010), respectively.

In the dry season, a larger fraction of the precipitation will be produced in the mixed–phase region, by riming of supercooled cloud droplets onto ice particles and by migration of water vapor to liquid water and ice particles. Ice at temperatures warmer than $-35^\circ \text{C}$ must be initiated by IN. Heterogeneous nucleation of ice particles usually occurs at temperatures below $-12^\circ \text{C}$ by contact of IN with or immersion into supercooled drops. However, abundant ice is found occasionally in growing cloud elements at higher temperatures, coming from a process where very few IN can lead to a much larger number of ice particles. Therefore, an important challenge is to identify these rare particles that can serve as IN at temperatures as high as $-5^\circ \text{C}$ (Hallett and Mossop 1974). These few newly formed ice particles will then collect supercooled cloud droplets and produce numerous ice splinters during the riming process, leading to a fast multiplication of ice particle concentrations, which increases precipitation. However, this ice multiplication is only effective if the supercooled cloud droplets are sufficiently large to have a considerable collision efficiency with ice particles. Therefore, in extremely polluted environments, where cloud droplet sizes are decreased, the riming efficiency is drastically reduced as well as the ice multiplication, leading to larger amounts of supercooled cloud water and the production of larger ice hydrometeors and even hail (Andreae et al. 2004). Biological IN (e.g., bacteria, fungal spores) will raise freezing temperatures, as they will freeze water at temperatures warmer than $-5^\circ \text{C}$ (Després et al. 2012). Additionally, larger concentrations of IN can significantly increase ice particle number and mass in cloud anvils under tropical humid conditions.

Depending on the location and season, the Amazon region offers ideal opportunities to study the contrast of cloud properties and aerosol–cloud interactions under near-pristine versus highly polluted conditions (Andreae et al. 2004; Pöschl et al. 2010).

**Biomass burning.** In central and southwest Amazonia, extensive areas of biomass burning are found during the dry (May–August) and dry-to-wet transition (September–October) seasons (Andreae et al. 2015). During these periods, logging, agriculture, and livestock are primarily managed by setting fire to clean out recently deforested regions or to prepare the soil in old pasture areas for livestock and seasonal crops. These fire outbreaks release large amounts of aerosol particles and CCN into the atmosphere (Artaxo et al. 2002; Roberts et al. 2003), while large patches of deforestation and pasture change the partitioning of latent and sensible heating at the surface. In particular, black carbon particles are emitted, which may influence precipitation formation (Gonçalves et al. 2015). The surface heating contrast between deforested and forested areas is enhanced during the dry season as a result of the low rainfall amounts. In consequence, more intense turbulent transients within the planetary boundary layer are generated, leading to higher cloud base heights (Fisch et al.
RESEARCH TOPICS AND RESULTING FLIGHT PATTERNS. In the framework of the general objectives of ACRIDICON–CHUVA, as outlined in the first section, five major research topics (a–e; realized by specific flight patterns) were pursued, which are briefly introduced in this section.

a) Cloud vertical evolution and life cycle (cloud profiling). The vertical evolution (from cloud base to anvil) of deep convective clouds was mapped during different stages of the clouds’ life cycle. Also, the initiation and development of precipitation particles in growing convective clouds were tracked. For this purpose, the properties of tropical deep convective cloud systems as a function of height above cloud base were measured under different levels of air pollution (i.e., trace gases and aerosol particles).

The corresponding schematic flight pattern to realize the vertical mapping is sketched in Fig. 2a. It started by probing the aerosol particle and trace gas distributions as well as the dynamic properties below cloud base (white arrows), then crossing the clouds at different altitudes (as icing allowed) and sampling the lower cloud parts (green arrows), ascending through the young developing cloud elements in the upshear boundary layer (inflow) and then—after stepwise climbing to the anvil—in the outflow region (inside and outside the anvil). The long endurance and high ceiling of HALO allowed surveying the outflow at several altitudes and in several directions from the convective core. Also entrainment and detrainment in the altitude regions between inflow and outflow (by circling around the cell at different altitude levels) were measured.

b) Cloud processing of aerosol particles and trace gases (inflow and outflow). The physical and chemical properties of trace gases, aerosol, and cloud particles in the inflow, in the interior, and in the outflow of deep convective clouds were measured, as well as their changes in the course of cloud evolution. For this purpose, the vertical redistribution of aerosol particles and trace gases by convective systems, the particle formation processes, and the evolution of aerosol properties in the fresh and aged outflow of convective cloud cells were investigated. Particle size distribution (PSD), mixing state, and particle chemical properties were characterized in inflow and outflow regions. Also, the role of black carbon (BC) particles as CCN and their deposition by precipitation and ice crystals were investigated.

The schematic flight pattern designed to cover this research topic is illustrated in Fig. 2b. The trace gases and aerosol particles were characterized by in situ and airborne remote sensing measurements, at first in the boundary layer (inflow) and then—after stepwise climbing to the anvil—in the outflow region (inside and outside the anvil). The long endurance and high ceiling of HALO allowed surveying the outflow at several altitudes and in several directions from the convective core. Also entrainment and detrainment in the altitude regions between inflow and outflow (by circling around the cell at different altitude levels) were measured.

c) Satellite and radar validation (cloud products). The validation of satellite data using dedicated ground-based radar measurements in combination with airborne remote sensing and in situ data are important to evaluate spaceborne cloud products. These data provide a more continuous (compared to sporadic aircraft campaigns) and expanded (as compared to the local ground-based radar data) view on the properties and evolution of tropical deep convective cloud systems. The strategy to validate the cloud products from satellite measurements is to compare, in a first step, the quantities directly measured by
satellite, ground-based radar, and airborne instrumentation (solar radiance, reflectivity). In a second step, satellite products such as cloud optical thickness, particle effective radius, liquid and ice water path, and thermodynamic phase derived by retrieval algorithms applied to ground-based radar, airborne, and satellite observations have been validated. One question to be answered is whether the combination of the aircraft remote sensing instruments with the ground-based radar and satellite data can actually improve the quality of the derived microphysical profiles of cloud properties. Furthermore, the in situ data measured by instruments mounted on the aircraft were compared with the data retrieved from the remote sensing measurements. Also, we investigated whether radiative transfer simulations based on the derived cloud profiles realistically represent the measured solar and terrestrial radiation budget of deep convective cloud systems and how important it is to consider the three-dimensional (3D) microphysical cloud structure in this regard.

For the validation of the satellite products, designated flights below and above clouds were carried out. Three flights were closely synchronized with overpasses of the A-Train set of satellite sensors, including Moderate Resolution Imaging Spectroradiometer (MODIS), CloudSat, Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and the Global Precipitation Measurement (GPM) satellite project. Additional legs through the cirrus outflow and for in situ sampling followed. To combine and compare ground-based radar and airborne in situ measurements, dedicated flight patterns above the radars were carried out. The flight patterns to cover this research topic were realized in combination with those introduced in Fig. 2.

d) Vertical transport and mixing (tracer experiment). This research topic investigated how air masses were transported, entrained, and scavenged by tropical deep convective cloud systems. An artificial tracer [perfluorocarbons (PFCs)] was released below the cloud and then sampled after it had spread. Additionally, a second tracer method was applied that used two atmospheric pollutants of common origin (e.g., emitted by biomass burning) but widely different atmospheric lifetimes—for example, CO and HCHO (formaldehyde). Both approaches allow studying vertical air mass transport associated with deep convective clouds and entrainment to characterize the type and degree of pollution in the air masses where convection occurs and to quantify the redistribution of air pollutants and their scavenging by tropical deep convective clouds.

After their release, the PFCs were probed by low-level horizontal flights measuring below the cloud after a certain amount of time had elapsed in order for the tracer to become homogeneously distributed. After one or two hours, the outflow was sampled. In the meantime, the entrainment region of the cloud was investigated. For quantification of scavenging of trace species in the convective cloud, the
concentration ratios of the trace gases and aerosol particles relative to the inert artificial (PFCs) and ambient (CO) tracers were measured in the inflow and outflow air. Therefore, the inflow air was characterized after release, dispersion, and mixing of the PFCs. These measurements were corroborated by measurements of chemical tracers of widely different atmospheric lifetimes (e.g., CO, HCHO) emitted from a common source (e.g., biomass burning). The change with time in the concentration ratio of the two tracers with a known emission ratio was used to determine the air mass age as function of height and location. The tracer experiments were combined with flights studying research topic b (see flight pattern shown in Fig. 2b).

e) Cloud formation over forested/deforested areas. The measurements of atmospheric variables such as wind, temperature, and water vapor as well as the microphysical and radiation parameters were used to evaluate the evolution of the atmospheric boundary layer and the cloud microphysical and radiative processes that are important to investigate the differences in convective cloud formation over forested versus deforested areas. The question to be answered is whether the cloud microphysical properties and processes over tropical rain forest and deforested regions were significantly different.

The flights during the ACRIDICON–CHUVA campaign allowed a statistical description of the clouds forming over tropical rain forest and deforested regions in polluted (biomass burning) and background environments. During several flights, measurements over tropical rain forest and deforested regions were conducted. Three layers were measured: base, middle, and top of the cloud.

One flight (on 27 September 2014) was specifically devoted to this research topic. Two forested/deforested regions were selected and different strategies measuring at the same level over different vegetation types were applied to avoid aerosol and thermodynamical differences between the measurements of the two vegetation types. The first flight track was over the Parque Nacional da Amazônia (4.2° S, 57° W); the flight was from west to east (see also Fig. 6) from the forest to the Transamazônica Road (BR-230) around Itaituba city. This flight path covered 65 km of forest and around 65 km of deforested region. The second flight path was over the Parque Nacional do Jamanxim (5.9° S, 55.3° W); the flight track was from north to south, from the national park to the deforested region around the BR-163 road that links Brasilia to Santarém and covered nearly the same path of 65 km over forest and deforested areas.

HALO INSTRUMENTATION AND FLIGHTS, AND GENERAL METEOROLOGICAL AND POLLUTION CONDITIONS. Instrumentation of HALO. The instruments installed on HALO during the ACRIDICON–CHUVA campaign are listed in Table 1. The details of the principle of operation of most of the listed devices are described in Wendisch and Brenguier (2013); additional references are given in Table 1. The cabin instruments were connected to respective inlets (gas sensors to a TGI, aerosol instruments to either HASI or the HALO-CVI, cloud
residuum sampler to the HALO-CVI), which were switched during the flight between HASI and HALO-CVI, depending on the specific purpose. Photos of the inlets and a sketch of the instrument locations in the cabin are presented in Figs. 3 and 4. Several instruments were installed in wing probes and inside the aircraft cabin to measure microphysical properties of aerosol particles, CCN and IN, droplets, ice crystals, and precipitation particles covering the size range from 5 nm (aerosol particles) to 6.4 mm (precipitation elements). Two instruments focused on the cloud active fraction of the aerosol population detecting aerosol particles that can be activated and grow to cloud droplets and measuring the ice-active particles.

The cloud and precipitation probes were one of the backbones of the HALO instrumentation during


<table>
<thead>
<tr>
<th>Instrument acronym</th>
<th>Measured quantity</th>
<th>Time resolution in Hz</th>
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<tbody>
<tr>
<td><strong>INLETS</strong></td>
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<tr>
<td>HALO-CVI</td>
<td>Inlet for cloud particles and residues ( D_v = 5–50 \mu m )</td>
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<td>HASI</td>
<td>HALO aerosol submicrometer inlet ( D ) up to a few mm (analysis ongoing)</td>
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<tr>
<td>TGI</td>
<td>Trace gas inlet</td>
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<td><strong>METEOROLOGY</strong></td>
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<tr>
<td>BAHAMAS</td>
<td>Pressure, temperature, wind, humidity, TAS aircraft position, attitude, heading, altitude</td>
<td>Up to 100</td>
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<td>BAHAMAS-SHARC</td>
<td>( H_2O ) mixing ratio (gas phase) ( R: 20–60,000 ), A: &lt;10%</td>
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<tr>
<td>MTP</td>
<td>Microwave radiances for temperature profiles ( R: \nu = 56.363, 57.612, 58.363 ) GHz</td>
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<tr>
<td>HAI [1, 2]</td>
<td>( H_2O ) gas phase concentration ( R: 1–40,000 ) ppmv (vapor) Up to 120</td>
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<td></td>
<td>Four channels: 2 × open path, 2 × closed path A: 4.3%</td>
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<td><strong>CHEMISTRY</strong></td>
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<tr>
<td>Aerosol impactor</td>
<td>Collects aerosol particles for microspectroscopy ( R: &gt;100 ) nm</td>
<td>Offline analysis</td>
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<td>C-ToF-AMS [3, 4]</td>
<td>Nonrefractory particle composition (organics, sulfate, nitrate, ammonium, chloride) ( R: D_v = 40 ) nm–1 ( \mu m ), A and P: ( \approx 30% )</td>
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<td>AMTEX</td>
<td>CO, O(_2) concentrations ( P: 2 ) ppb; A: 5%</td>
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<td>PFCs (( C_{F_{12}}, C_{F_{14}} ))</td>
<td>( P: 1 ) ppq; A: 3%</td>
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<td>PAN (peroxacytrol nitrate), ( SO_2 )—concentration ( P: 5 ) ppt; A: 7%</td>
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<td>( HNO_3 ), HONO concentrations ( P: 30 ) ppt; A: 10%</td>
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<td>PERTRAS</td>
<td>PFCs: perfluorocarbons</td>
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<td>NO, NO(_y) ( R: 5 ) pmol mol(^{-1})–60 nmol mol(^{-1})</td>
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<td></td>
<td>NO: A: ( \approx 8% ) at 50 nmol mol(^{-1})</td>
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<td></td>
<td>NO(_y): A: ( \approx 7% ) at 450 nmol mol(^{-1})</td>
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<td>miniDOAS [5]</td>
<td>Spectral radiance to derive trace gas concentrations: HCHO, BrO, IO, ( ClO_2 ), ( C_2H_2O_2, CH_4 )</td>
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<td>( BrO_2, I_2, O_3, O_4, NO_2, HONO, H_2O, CO_2 )</td>
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<td><strong>MICROPHYSICS</strong></td>
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<td>Aerosol particles</td>
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<tr>
<td>SNOOPY (SP2) [6]</td>
<td>rBC mass/number concentration, aerosol PSD ( R: rBC, mass: 0.26–125 ) fg (65–510 nm)</td>
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</tbody>
</table>
the ACRIDICON–CHUVA campaign. They were installed beneath the wings of HALO (see Fig. 5). All cloud probe inlet entries and tips were modified to minimize the area susceptible to shattering of ice particles. Further, the probes were equipped with the "particle-by-particle option"; that is, each particle was recorded individually including its own timestamp, which made a particle inter–arrival time analysis and a subsequent removal of most of the shattered ice crystal fragments possible. A comparison between the CAS using an inlet and the corresponding open–path CDP yielded good agreement, showing that shattering—which was especially feared to happen at the inlet of the CAS—was successfully minimized. HALO flights. Fourteen scientific flights (labeled AC07 to AC20) with a total number of 96 flight hours were conducted in Brazil over Amazonia during the ACRIDICON–CHUVA campaign (Table 3). More than 40 additional flight hours were spent for electromagnetic noise and instrument testing (AC01

<table>
<thead>
<tr>
<th>Table 1. Continued.</th>
<th>Measured quantity</th>
<th>R: range of measurement</th>
<th>Time resolution in Hz</th>
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<tr>
<td>Instrument acronym [Additional reference]</td>
<td></td>
<td></td>
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<tr>
<td>AMETYST</td>
<td>Particle number concentration</td>
<td>R: (D_v = 5 \text{ nm}–1 \text{ (\mu m)})</td>
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</tr>
<tr>
<td>PSAP</td>
<td>Particle absorption coefficient</td>
<td>R: (\lambda = 467, 530, 660 \text{ nm})</td>
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</tr>
<tr>
<td>DMPS and OPC</td>
<td>Aerosol PSD</td>
<td>R: (D_v = 5–350 \text{ nm} \text{ and } 250 \text{ nm}–3 \text{ (\mu m)})</td>
<td>1</td>
</tr>
<tr>
<td>Permanently behind CVI</td>
<td>Residual particle number concentration</td>
<td>R: (D_v = 10 \text{ nm}–3 \text{ (\mu m)})</td>
<td>0.33</td>
</tr>
<tr>
<td>PSAP</td>
<td>Residual particle absorption coefficient</td>
<td>R: (\lambda = 567 \text{ nm})</td>
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<tr>
<td>UHSAS</td>
<td>Residual PSD</td>
<td>R: (D_v = 100 \text{ nm}–1 \text{ (\mu m)})</td>
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<td>Electrometer</td>
<td>Drop charge</td>
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<td>0.33</td>
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<tr>
<td>UHSAS-A</td>
<td>Aerosol PSD</td>
<td>R: (D_v = 60 \text{ nm}–1 \text{ (\mu m)})</td>
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<tr>
<td>PCASP-100X</td>
<td>Aerosol PSD</td>
<td>R: (D_v = 0.12–3.5 \text{ (\mu m)})</td>
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<tr>
<td>CCN and IN</td>
<td>CCN concentration</td>
<td>R: (S = 0.13% – 0.53%)</td>
<td>1</td>
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<tr>
<td>FINCH</td>
<td>Total and biological IN concentrations</td>
<td>R: (T \geq –40 \text{°C}, \text{ saturation ratio wrt ice } \leq 2)</td>
<td>0.1</td>
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<td>SP2 [6]</td>
<td>rBC mass concentration, aerosol PSD</td>
<td>R: (D_v = 120–360 \text{ nm})</td>
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<tr>
<td>Cloud particles</td>
<td>Cloud PSD and shape, liquid water content</td>
<td>R: (D_v = 0.5–50 \text{ (\mu m)})</td>
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<tr>
<td>PHIPS-HALO</td>
<td>Cloud PSD, stereoscopic particle imaging</td>
<td>R: (D_v = 10 \text{ (\mu m)}–1 \text{ mm})</td>
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<td>SID-3</td>
<td>Single particle scattering phase function</td>
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<td>Cloud particles</td>
<td>Cloud PSD, ice particle shape,</td>
<td>R: (D_v = 5–50 \text{ (\mu m)})</td>
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<tr>
<td>surface roughness</td>
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<tr>
<td>NIXE–CAPS</td>
<td>Cloud PSD, asphericity</td>
<td>R: (D_v, D_{\Delta v} = 0.6–50 \text{ (\mu m)})</td>
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<tr>
<td>CAS-DPOL</td>
<td>Cloud PSD</td>
<td>R: (D_v = 15–950 \text{ (\mu m)}; \Delta D_v = 15 \text{ (\mu m)})</td>
<td>1</td>
</tr>
<tr>
<td>CIPgs</td>
<td>Cloud PSD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCP</td>
<td>Cloud PSD</td>
<td>R: (D_v = 3–50 \text{ (\mu m)}; \Delta D_v = 1–2 \text{ (\mu m)})</td>
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<tr>
<td>CIPgs</td>
<td>Cloud PSD</td>
<td>R: (D_v = 15–950 \text{ (\mu m)}; \Delta D_v = 15 \text{ (\mu m)})</td>
<td>1</td>
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<td>Precipitation</td>
<td>Precipitation PSD</td>
<td>R: (D_v = 100–6,400 \text{ (\mu m)}; \Delta D_v = 100 \text{ (\mu m)})</td>
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<td>RADIATION</td>
<td>Spectral radiance</td>
<td>R: (\lambda = 400–2,500 \text{ nm}; \Delta \lambda = 5–10 \text{ nm})</td>
<td>30–100</td>
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<td>specMACS [7]</td>
<td>Spectral irradiance (upward and downward)</td>
<td>R: (\lambda = 350–2,200 \text{ nm}; \Delta \lambda = 2–16 \text{ nm})</td>
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<td>SMART [8, 9, 10]</td>
<td>Spectral radiance (upward, FOV = 2.1°)</td>
<td>R: (\lambda = 350–2,200 \text{ nm}; \Delta \lambda = 2–16 \text{ nm})</td>
<td>2</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>3D</td>
<td>Three dimensional</td>
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<tr>
<td>2D</td>
<td>Two dimensional</td>
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<tr>
<td>AC</td>
<td>ACRIDICON–CHUVA</td>
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<tr>
<td>ACRIDICON</td>
<td>Aerosol, Cloud, Precipitation, and Radiation Interactions and Dynamics of Convective Cloud Systems</td>
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<tr>
<td>AMAZE</td>
<td>Amazonian Aerosol Characterization Experiment</td>
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<tr>
<td>AENEAS</td>
<td>Atmospheric Nitrogen Oxides Measuring System</td>
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<td>ARM</td>
<td>Atmospheric Radiation Measurement</td>
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<td>AMETYST</td>
<td>Aerosol Measurement System</td>
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<td>AMTEX</td>
<td>Atmospheric Tracer Experiment</td>
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<td>ATTO</td>
<td>Amazon Tall Tower Observatory</td>
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<tr>
<td>BAHAMAS</td>
<td>Basic HALO Measurement and Sensor System</td>
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<tr>
<td>BC</td>
<td>Black carbon</td>
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<tr>
<td>rBC</td>
<td>Refractory black carbon</td>
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<td>CALIPSO</td>
<td>Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations</td>
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<tr>
<td>CAPE</td>
<td>Convective available potential energy</td>
<td></td>
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<tr>
<td>CAS-DPOL</td>
<td>Cloud Aerosol Spectrometer with Detector for Polarization</td>
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<tr>
<td>CAPS</td>
<td>Cloud, aerosol, and precipitation spectrometer</td>
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<tr>
<td>CCN</td>
<td>Cloud condensation nuclei</td>
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<tr>
<td>CCP</td>
<td>Cloud combination probe</td>
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<tr>
<td>CDP</td>
<td>Cloud droplet probe</td>
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<td>CHUVA</td>
<td>Cloud Processes of the Main Precipitation Systems in Brazil: A Contribution to Cloud Resolving Modeling and to the GPM (Global Precipitation Measurement)</td>
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<tr>
<td>CIP</td>
<td>Cloud imaging probe</td>
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<td>CPC</td>
<td>Condensation particle counter</td>
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<tr>
<td>C-ToF-AMS</td>
<td>Compact time-of-flight aerosol mass spectrometer</td>
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<tr>
<td>CVI</td>
<td>Counterflow virtual impactor</td>
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<tr>
<td>DMPS</td>
<td>Differential mobility particle sizer</td>
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<tr>
<td>dTDLAS</td>
<td>Direct tunable diode laser absorption spectroscopy</td>
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<tr>
<td>miniDOAS</td>
<td>Miniaturized differential optical absorption spectroscopy</td>
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<tr>
<td>DSD</td>
<td>Droplet size distribution</td>
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<td></td>
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<tr>
<td>FOV</td>
<td>Field of view</td>
<td></td>
<td></td>
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<tr>
<td>FINCH</td>
<td>Fast ice nuclei chamber</td>
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<tr>
<td>GoAmazon2014/5</td>
<td>Observations and Modeling of the Green Ocean Amazon</td>
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<tr>
<td>GPM</td>
<td>Global Precipitation Measurement</td>
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<tr>
<td>HAI</td>
<td>Hygrometer for atmospheric investigations</td>
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<tr>
<td>HALO</td>
<td>High Altitude and Long Range Research Aircraft</td>
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<tr>
<td>HASI</td>
<td>HALO aerosol submicrometer inlet</td>
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<tr>
<td>HIAPER</td>
<td>High-Performance Instrumented Airborne Platform for Environmental Research</td>
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<tr>
<td>IN</td>
<td>Ice nuclei</td>
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<tr>
<td>INPE</td>
<td>Instituto Nacional de Pesquisas Espaciais</td>
<td></td>
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<tr>
<td>IOP2</td>
<td>Second intensive observation period 2</td>
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<tr>
<td>ITMS</td>
<td>Ion trap mass spectrometer</td>
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<tr>
<td>LBA</td>
<td>Large Scale Biosphere Atmosphere Experiment in Amazonia</td>
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</tr>
<tr>
<td>LWC</td>
<td>Liquid water content</td>
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<tr>
<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
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</table>
to AC04) needed to obtain the campaign certification and the ferry flights from Germany to Manaus (AC05 and AC06) and back to Germany (AC21 and AC22). A summary of the flights performed in Brazil, including information on the research topics pursued during each flight, is given in Table 3. A narrative record of the campaign is available in blog form at http://acridicon-chuva.weebly.com.

The long endurance of HALO allowed covering a wide geographic area and different pollution conditions within one flight (see the flight tracks illustrated in Fig. 6). The high ceiling altitude and the long endurance of HALO were utilized on most flights, which becomes obvious from the time series of flight altitudes presented in Fig. 7. Half of the flights took more than 7 h, and occasionally an altitude of 15 km was reached. On the other hand, the combination of long endurance and high ceiling altitude made it possible to study the life cycle of individual convective clouds with high vertical resolution over a long time.

General meteorological and pollution conditions. The annual cycle of the sun produces a large-scale, low-level convergence movement from the central part (during austral summer) to the northwest part (spring) of South America and this controls the Amazonian convection and rainfall (Horel et al. 1989). The field campaign was conducted during the transition from the dry to the onset of the wet season,
Fig. 4. Sketch of the cross section (top view) of HALO. (a) The positions of the instrument racks installed in the cabin are indicated in red. Additional technical equipment such as pumps or reference systems are indicated in blue (PMS_PRU is the major data acquisition for PMS probes). (b) Inlets and apertures mounted/installed on the upper (blue) and lower (red) fuselage.

Table 3. Summary of flights with HALO performed during the ACRIDICON–CHUVA campaign. The research topics covered and the corresponding flight patterns as introduced in the section on “Research topics and resulting flight patterns” are indicated by letters a–e with “a” cloud vertical evolution and life cycle (cloud profiling), “b” cloud processing of aerosol particles and trace gases (inflow and outflow), “c” satellite and radar validation (cloud products), “d” vertical transport and mixing (tracer experiment), and “e” cloud formation over forested/deforested areas.

<table>
<thead>
<tr>
<th>No.</th>
<th>Date in 2014</th>
<th>Research topic</th>
<th>Ceiling altitude (km)</th>
<th>Time span</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC07</td>
<td>6 Sep</td>
<td>a</td>
<td>13.9</td>
<td>7 h, 35 min</td>
<td>Test of flight strategy</td>
</tr>
<tr>
<td>AC08</td>
<td>9 Sep</td>
<td>a</td>
<td>13.8</td>
<td>5 h, 30 min</td>
<td>Coordinated with G1</td>
</tr>
<tr>
<td>AC09</td>
<td>11 Sep</td>
<td>a</td>
<td>12.6</td>
<td>6 h, 10 min</td>
<td>Clean conditions</td>
</tr>
<tr>
<td>AC10</td>
<td>12 Sep</td>
<td>c</td>
<td>14.4</td>
<td>7 h, 25 min</td>
<td>Along A-Train path</td>
</tr>
<tr>
<td>AC11</td>
<td>16 Sep</td>
<td>b, d</td>
<td>12.9</td>
<td>7 h, 25 min</td>
<td>Tracer experiment</td>
</tr>
<tr>
<td>AC12</td>
<td>18 Sep</td>
<td>a</td>
<td>13.8</td>
<td>6 h, 15 min</td>
<td>Polluted conditions</td>
</tr>
<tr>
<td>AC13</td>
<td>19 Sep</td>
<td>a</td>
<td>12.9</td>
<td>6 h, 30 min</td>
<td>Polluted conditions</td>
</tr>
<tr>
<td>AC14</td>
<td>21 Sep</td>
<td>c</td>
<td>15.2</td>
<td>7 h, 15 min</td>
<td>Coordinated with G1; Along A-Train path</td>
</tr>
<tr>
<td>AC15</td>
<td>23 Sep</td>
<td>c, b</td>
<td>13.8</td>
<td>7 h, 20 min</td>
<td>Along A-Train path</td>
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<tr>
<td>AC16</td>
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<td>b, d</td>
<td>13.2</td>
<td>6 h, 50 min</td>
<td>Tracer experiment</td>
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<tr>
<td>AC17</td>
<td>27 Sep</td>
<td>e</td>
<td>8.1</td>
<td>6 h, 40 min</td>
<td>Comparison with GPM</td>
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<tr>
<td>AC18</td>
<td>28 Sep</td>
<td>a</td>
<td>14.4</td>
<td>6 h, 50 min</td>
<td>Clean conditions</td>
</tr>
<tr>
<td>AC19</td>
<td>30 Sep</td>
<td>a</td>
<td>13.8</td>
<td>7 h, 15 min</td>
<td>Marine conditions</td>
</tr>
<tr>
<td>AC20</td>
<td>1 Oct</td>
<td>b, a</td>
<td>14.4</td>
<td>7 h, 5 min</td>
<td>Coordinated with G1</td>
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a period when local farmers and regional forestry industries set fire to pastures and freshly cut forest regions in order to prepare the land for the upcoming rainfalls.

To describe the general weather and pollution conditions during the ACRIDICON–CHUVA campaign, Fig. 8 shows time series of selected meteorological variables (air temperature, wind direction, precipitation) of the concentrations of pollution tracers such as CO and BC, as well as of several aerosol parameters (particle number concentration and size distribution) from measurements at the Amazon Tall Tower Observatory (ATTO) site, which is located 150 km northeast of Manaus (Andreae et al. 2015). The data were taken at 60 m above ground level. At the ATTO site, meteorological, trace gas, and aerosol measurements are regularly conducted above the forest canopy within the framework of a long-term measurement program. Periods of individual flights are marked by vertical lines and labeled with flight numbers (see also Table 3). The general meteorological conditions during September 2014 were characterized by prevailing easterly wind directions, relatively high temperatures, and low rainfall with little day-to-day variability. Aerosol and CO time series show an oscillation of the atmospheric state between moderate and substantial anthropogenic pollution levels.

The vertical temperature profiles measured during all flights of the ACRIDICON–CHUVA campaign were rather similar (not shown). The stratosphere was not reached during the flights, since the cold point tropopause is usually located around 18 km in the tropics. In contrast, the relative humidity fields strongly depended on the actual water vapor situation.

Cloud microphysical in situ measurements in warm clouds. A set of DSDs was measured in warm convective clouds. Most clouds were penetrated by a visual selection of tops of growing convective...
elements. This assured that clouds were penetrated at the same phase of their life cycle and that no precipitation fell from above into the measured cloud volume. Respective results of microphysical measurements are plotted as a function of altitude in Figs. 9–11.

Figure 9a presents the DSD data measured at different altitudes for a relatively clean (pristine, background) cloud case (AC09), whereas the DSDs plotted in Fig. 9b show measurements collected in polluted (biomass burning, smoky) convective clouds observed during AC12. In the clean clouds the droplets grow to large drops in the millimeter-size range and form rain, whereas for the polluted case the cloud droplets do not coalesce and form only negligible amounts of precipitation-size drops. The polluted clouds contain more small and fewer large droplets compared to the pristine clouds. These statements are confirmed by Fig. 10, which shows selected DSDs from the same flights, which are representative for the cloud top (Fig. 10a), the middle of the clouds (Fig. 10b), and the cloud base (Fig. 10c).
These findings are underlined by corresponding plots of the vertical profiles of integrated cloud microphysical properties such as total droplet number concentrations, droplet effective radius, and LWC (Fig. 11). The cloud droplet number concentrations were low and continued to decrease further with height owing to coalescence in the clean clouds (see Fig. 11a). These features are opposite in the polluted case because of suppressed coalescence (Fig. 11b). The vertical profiles of the droplet effective radius illustrate that the cloud droplets grow quickly with height for the clean clouds and, vice versa, grow slowly with height for the polluted case (see Figs. 11c and 11d). The LWC plots give evidence that rain develops above 2.7 km above ground in the clean clouds (open red diamonds in Fig. 11e) and that rain is completely suppressed at least up to 6-km altitude in polluted clouds (see Fig. 11f).

**Remote sensing of cloud thermodynamic phase.** The vertical distribution of the thermodynamic phase is directly linked to the formation of precipitation. Therefore, specMACS observed the cloud sides to identify the depth of the mixed-phase layer. The measurement setup applied for the observations of spectral solar radiation reflected from cloud sides using the

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**Fig. 9.** Number size distributions of droplets in warm convective clouds measured with the NIXE–CAPS instrument. The colors of the lines indicate altitude above ground level at which the measurements were taken. (a) Flight AC09 (clean case) and (b) flight AC12 (polluted cloud influenced by biomass burning).

**Fig. 10.** Number size distribution of droplets in warm convective clouds measured with the NIXE–CAPS instrument during flight AC09 (clean case, solid line) and during flight AC12 (polluted conditions, dashed line) for different flight altitudes: (a) close to cloud top, (b) middle of cloud, and (c) near cloud base. The data were selected from Fig. 9.
Fig. 11. (a),(b) Droplet number concentration; (c),(d) effective radius; and (e),(f) liquid water content in warm convective clouds as a function of altitude calculated from the droplet size distributions shown in Fig. 9. (left) The data from flight AC09 (clean case) and (right) from flight AC12 (polluted cloud influenced by biomass burning). In (e) and (f) black symbols show the cloud LWC (considering particles with diameter smaller than 50 µm, measured by the CAS-DPOL), red symbols indicate rain LWC (including particles with diameter equal or larger than 50 µm, from CIPgs). The rain is suppressed in the polluted case (f).
imaging spectrometers of specMACS is illustrated in Fig. 12. HALO passes a cloud and specMACS observes a vertical column of pixels and records the spectral radiances reflected by the cloud. In this way, specMACS takes a series of consecutive snapshots of the reflected spectral solar radiances in the pixel column during the flyby, which are then used to reconstruct spectral reflected radiance maps of the cloud side. The changes of the roll angle of the aircraft during the flyby are obvious in Fig. 12. The potential of such cloud side observations of reflected solar radiances using specMACS is exemplified in Fig. 13. In a first step, a cloud mask excludes shaded areas of the cloud from further analysis (gray colored areas in Fig. 13a). Then the spectral slope of the reflected radiance measurements at 1.55 and 1.7 µm for each pixel of the 2D image is calculated, from which a phase index is derived as described by Jäkel et al. (2013). Negative values of the phase index indicate liquid water droplets; positive values hint at ice crystals. Figure 13a shows a corresponding 2D image of the phase index corrected with respect to the flight attitude. The transition between liquid water and ice thermodynamic phases is well defined by the vertical distribution (approximated by the elevation) of the phase index as shown in Fig. 13b. The separation between lower-level liquid water and upper-level ice portions of the convective cloud and thus the vertical extension of the mixed-phase layer is characterized by a strong increase of the phase index from negative to positive values. Stereogrammetry methods have been applied to determine the height of the mixed-phase layer. The analyzed example shown in Figs. 12 and 13 exhibits a mixed-phase layer between 5.5 and 7.6 km altitude, which corresponds to a temperature range of –3° to –11°C.

Fig. 12. Cloudside observations of reflected solar radiances for a cloud during flight AC20. The black vertical line indicates a dark-current measurement. Changes of the elevation angle above/below horizon results from variable roll angles of the aircraft.

Fig. 13. Phase index derived from the specMACS measurements of cloudside reflected radiances for the same cloud as in Fig. 12 (from flight AC20). (a) Time series of vertical distribution of the phase index (side view), recorded during a flyby. The different colors represent values of the phase index. The dark gray areas indicate cloudless portions or land surface; the light gray areas represent shadow zones of the cloud sides, which are excluded from further analysis by an automatic cloud mask algorithm. These shadowed areas are not suitable for phase index analysis. The black vertical line indicates a dark-current measurement. (b) Vertical profile of phase index; three approximate altitudes (5.5, 7.6, and 11.7 km) are allocated to vertical pixels.
Cloud microphysical in situ measurements in cold clouds. Figure 14 shows an example of data from the PHIPS-HALO instrument. The left panel shows results from measurements collected in ambient in situ cirrus and the right panel contains data sampled in an anvil outflow. The in situ cirrus was probed at an altitude of 12 km in a temperature below −40°C. The outflow was sampled also at an altitude of 12 km, with a temperature of −47°C. Thus both cases were sampled approximately at the same temperatures but show different ice crystal habits. This indicates that the formation of the ice crystal took place at different temperatures; that is, the outflow ice particles have been transported from below but measured at the cirrus temperature range. It further demonstrates that the microphysical properties of ice particles in anvil outflows of convective cloud systems differ significantly from those of ambient in situ cirrus. While in situ cirrus is dominated by small ice particles, bullet rosettes, and bullet rosette aggregates, anvil outflows were largely composed of plates and plate aggregates. This result clearly reflects the strong vertical transport that is prevailing in tropical convective systems. Platelike ice crystals that were heterogeneously nucleated on solid aerosol particles and grown in the lower, warmer parts of the system (warmer than −37°C) were lifted to the cold outflows (colder than −50°C).

Fig. 15. Time series plot of CCN concentrations and altitude during flight AC08. The green markers represent the CCN measurements performed at the T3 measurement site near Manacapuru. Particle number concentrations have been normalized to standard air pressure (1000 hPa) and temperature (273.15 K).

Fig. 14. Statistical analysis of the ice microphysical properties of ambient in situ cirrus sampled during flight AC12 and of an anvil outflow of a tropical convective system sampled during flight AC16. The analysis is based on stereoscopic images taken by the PHIPS-HALO probe, which was newly developed for HALO.
where they are mixed with in situ grown columnar crystals. In conjunction with cloud process modeling, the statistical analysis of platelike ice crystals in the cold outflows can be used to understand the effect of pollution on the dynamics in convective systems.

**Cloud condensation nuclei (CCN).** The number concentration of CCN was measured using a two-column continuous-flow streamwise thermal gradient CCN counter [CCN-200, Droplet Measurement Technologies (DMT) Inc., Boulder, Colorado]. The pressure in the instrument was kept constant at 270 hPa with a specially developed constant pressure inlet, connected to the HASI inlet. To illustrate the CCN data obtained during ACRIDICON–CHUVA, the time series of CCN concentration at a supersaturation of $S = (0.53\% \pm 0.02\%)$ and the aircraft flight altitude are plotted in Fig. 15. These data were collected in clear air outside of clouds. The measurements were performed downwind of Manaus in the region over Manacapuru at altitudes from about 1 to about 13 km (flight AC08 on 9 September 2014). The green markers represent the CCN concentration (interpolated to the same supersaturation) measured at the ground-based measurement station at Manacapuru (T3), which were collected as part of the GoAmazon2014/5 campaign [data from ARM database: www.arm.gov; see also Martin et al. (2016)]. The CCN measurements taken when HALO was flying in the boundary layer near the ground station are in good agreement with the ground-based CCN measurements at T3.

The mean value and the standard deviation of the CCN concentration in the boundary layer up to about 2-km altitude are $(543 \pm 251)$ cm$^{-3}$, indicating the presence of pollution-derived aerosol particles originating from the Manaus area. No strong peaks of CCN concentrations were observed, which suggests rapid aging and distribution of local emissions. Above

![Fig. 16. Profiles of mixing ratios of (a) O$_3$, (b) NO$_2$, (c) NO$_y$, (d) CO, and (e) HCHO measured during flight AC11 on 16 Sep 2014. The southern leg of AC11 was performed under notably more polluted conditions (open red circles) than the northern leg (open blue diamonds). The cluster points indicate the variability of concentrations for individual altitudes measured at constant flight levels. Unfortunately, during flight AC11, the NO detection channel was not working.](image-url)
the boundary layer, CCN concentrations declined to a minimum at around 5-km altitude and then increased again in the upper troposphere. The origin of these upper-tropospheric aerosols is still uncertain: they may be the result of long-range transport at high altitudes or they may have been produced in cloud outflows.

**Trace gas data.** Figure 16 displays vertical profiles of the mixing ratios of $O_3$, NO$_2$, NO$_y$ (= NO, NO$_2$, NO$_3$, HNO$_3$, …), CO, and HCHO measured during the northern and southern legs of flight AC11 on 16 September 2014. Here the elevated mixing ratios of NO$_2$, NO$_y$, CO, and HCHO detected during the southern leg (open red circles), as compared to the northern leg (open blue diamonds), are indicative of conditions affected by biomass burning (Crutzen and Andreae 1990). The trace gases—NO$_2$, NO$_y$, CO, and HCHO—are either directly emitted by biomass burning (CO, NO, and HCHO) or produced by photo-oxidation within the biomass burning plume (NO$_2$, NO$_y$, CO, and HCHO). In fact, the visual observations made from the aircraft during AC11 indicated several massive biomass burning plumes in the southern part of the State of Amazonas and virtually none in the northern part of Amazonas and southern part of Roraima. The measured trace gas values will allow us to infer emission ratios of some key pollutants from biomass burning as well as studies on aging and photochemical processing of the investigated air masses. The elevated mixing ratios of the pollutants up to the top of the boundary layer (around 950 m) are due to the Manaus city plume.

**SUMMARY.** The ACRIDICON–CHUVA campaign was successfully performed in an area spanning across much of the Amazon basin in September and October 2014. The campaign aimed at studying the evolution of tropical convective clouds over the Brazilian rain forest and at investigating related interactions with aerosol particles and trace gases by a combination of dedicated airborne and ground-based, in situ, and remote sensing measurements. Ground-based stations and the new German research aircraft HALO measured the atmospheric and cloud properties in concert with the meteorological, aerosol, and radiative properties and some key trace gases. This paper gives an overview of the scientific motivation and objectives of the ACRIDICON–CHUVA campaign with a focus on the airborne observations with HALO. Furthermore, the instrumentation and flight patterns of HALO are introduced. HALO proved to be a valuable research tool, carrying a comprehensive scientific payload, flying across much of the Amazon basin, and reaching 15-km flight altitude. A particular advantage of HALO is its extended endurance of up to 8 h, which allowed us to flexibly adjust flight patterns to the actual cloud situations.

Some selected measurement results are presented. They indicate the scientific potential of the collected in situ and remote sensing observations to characterize the evolution of vertical profiles of cloud microphysical parameters, in combination with concurrent aerosol and trace gas measurements. The impact of environmental pollution on the cloud droplet size distribution and its vertical dependence was quantified, showing more small and fewer large cloud droplets in polluted conditions and the related suppression of precipitation. First results of a new spectral imaging technique observing cloud side reflection of solar radiation showed promising results in distinguishing between liquid water droplets and ice crystals. This method shall be further developed to deliver droplet/ice crystal sizes as a function of altitude and cloud temperature in order to reveal typical signatures in the evolution of tropical convective clouds. Elevated CCN concentrations at higher altitudes were identified; their origin will have to be investigated in future work. The characteristics of ice crystals in the outflow were studied and compared with natural cirrus cloud properties. Vertical transport processes were identified by profile measurements of trace gases.

The reader is invited to visit the ACRIDICON–CHUVA website at [www.uni-leipzig.de/~meteo/acridicon-chuva](http://www.uni-leipzig.de/~meteo/acridicon-chuva). The data are stored in the HALO database ([https://halo-db.pa.op.dlr.de](https://halo-db.pa.op.dlr.de)), which also describes the access to the measurement results. The general data policy is defined in a protocol available at [www.uni-leipzig.de/~meteo/acridicon-chuva/DataProtocol.html](http://www.uni-leipzig.de/~meteo/acridicon-chuva/DataProtocol.html).

This paper reports preliminary results and it marks just the beginning of the detailed data analysis. It is intended to serve as a reference for a series of detailed scientific publications planned for the future.

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Instituto Nacional de Pesquisas da Amazônia (INPA) for the local logistic help prior to, during, and after the campaign. Thanks also to the Brazilian Space Agency [Agência Espacial Brasileira (AEB)] responsible for the program of cooperation (CNPq license 00254/2013-9 of the Brazilian National Council for Scientific and Technological Development). H. Schlager, J. Schneider, C. Mahnke and R. Weigel received funding by the German BMBF within the joint ROMIC-project SPITFIRE (01LG1205A). A special thanks to the DLR Flight Experiments team and pilots. We appreciate the support of the colleagues from enviscope GmbH for their valuable help in certifying and installing the numerous instruments for HALO.

REFERENCES


The boreal forest atmosphere provides an ideal locale to study aerosol and cloud microphysical processes. In this clean environment, the contribution of biogenic emissions and subsequent increases in secondary aerosol number (e.g., Kulmala et al. 2007, 2013) and mass (e.g., Tunved et al. 2006) enables assessment of the importance of natural aerosol in the aerosol–cloud interactions. Anthropogenic influences and signatures in aerosol particle size distributions (PSDs) are evident even at the cleanest sites (Carslaw et al. 2013). However, with a suitably long time series, analyses of aerosol–cloud interactions in such an environment can be used for assessing the role of both natural and anthropogenic emissions in global climate, especially over boreal and Arctic regions, which are experiencing drastic changes because of the ongoing climate change (Epstein et al. 2013; Koenigk et al. 2013).

The largest uncertainty in climate predictions comes from aerosol–cloud interactions (Boucher et al. 2013). A lack of comprehensive observations of cloud and precipitation systems in different climatic regimes is one of the key reasons for this uncertainty (Stephens and Kummerow 2007). Because of the complexity of different feedback mechanisms linking global climate with aerosols, trace gases, and precipitation, regional and global climate models are unable to reliably predict precipitation patterns and their changes (Rosenfeld et al. 2008; Ren et al. 2013). As a result, climatologically meaningful connections between aerosols, clouds, and precipitation have not yet been established (Stevens and Feingold 2009). An approach postulated to address this problem is the “deployment of arrays of ground-based remote sensors that can both vertically and temporally resolve the aerosol, clouds, precipitation and the meteorological state” and to document cloud and precipitation processes in different regimes (Stevens and Feingold 2009, p. 611). This holistic approach capturing the life cycles of aerosols, clouds, and precipitation was adopted for the campaign Biogenic Aerosols–Effects on Clouds and Climate (BAECC; Petäjä 2013).
During BAECJ, the U.S. Department of Energy (DOE)’s Atmospheric Radiation Measurement (ARM) Program deployed their Second ARM Mobile Facility (AMF2) in Hyytiälä, Finland (61°51’ N, 24°17’ E), for an 8-month intensive measurement campaign from February to September 2014 (Fig. 1). Hyytiälä hosts the Station for Measuring Ecosystem–Atmosphere Relations II (SMEAR II; Hari and Kulmala 2005; see sidebar on “Hyytiälä: History and significant scientific advances”). The primary research goal of BAECJ is to understand how biogenic aerosols affect cloud microphysical properties.

**OBSERVATIONS.** To reach the holistic research goals, a comprehensive measurement approach is required. During BAECJ this was provided through the complementary strengths of SMEAR II and AMF2 capabilities. SMEAR II ecophysiological measurements and in situ observations of the physical, chemical, and optical properties of aerosol particles and ions were complemented with the ground-based active remote sensing capacity of the AMF2 radar and lidar systems. Additional supplementary observations on aerosol chemical composition, aerosol precursors, nanoparticle concentrations, precipitation properties, and aerosol and water vapor vertical profiling were provided by collaborators from the United States and Europe, both for the whole observation period and during intensive observation periods (IOPs; Fig. 1). During IOPs, a total of 152 flight hours with Cessna and Skyvan aircraft provided in situ data on trace gases, aerosol particle concentration, and aerosol chemical composition. Traditional meteorological soundings (4 day−1) were enhanced with novel miniatu0nized solar radiation, charge, and turbulence sensors during two of the IOPs. In addition to the AMF2 radars, precipitation and cloud properties above Hyytiälä were provided by the Finnish Meteorological Institute (FMI) operational dual-polarization weather radar once every 15 min. One IOP was dedicated to documenting snowfall microphysics through a combination of multifrequency (C, X, Ka, and W band) radar, microwave radiometer (MWR), and lidar measurements supplemented by a comprehensive suite of surface-based precipitation observations. For a comprehensive list of observations, see Table SB1.

Both SMEAR II and the AMF2 Aerosol Observation System (Jefferson 2011) performed in situ measurements of aerosols during BAECJ, including cloud condensation nuclei (CCN) concentrations and optical properties. Datasets collected by both facilities have been compared for quality assurance and control. Moreover, additional in situ measurements deployed in the same area allow for the assessment of small-scale spatial variability in aerosol concentration and size distribution.

On the regional scale, the representativeness of the datasets will be evaluated by the continuous and coordinated aerosol observations performed at five other SMEAR aerosol observation network sites in Finland and by the four aircraft IOPs. The existing 20-yr-long measurement data from SMEAR II enables...
the assessment of the representativeness of the data collected during the BAECC period. The utilization of the SMEAR observation network, Aerosols, Clouds, and Trace Gases Research Infrastructure Network (ACTRIS), and Global Atmospheric Watch data provides avenues for expanding the analysis to an even larger extent. The data from SMEAR II are available via Junninen et al. (2009) and from smartSMEAR (2016). AMF2 data are available from the ARM data archive (ARM 2015).

EMISSIONS TO AEROSOLS. Of all biomes, the boreal forests appear to have the largest biogeophysical effect on the annual-mean global temperature (Bonan 2008). The forest is a net sink for carbon dioxide consumed in vegetation photosynthesis. Furthermore, the boreal environment is a substantial source of biogenic volatile organic compounds (BVOCs), which can affect tropospheric ozone (Atkinson and Arey 2003), and BVOCs are associated with frequent secondary aerosol formation (e.g., Kulmala et al. 2001; Dal Maso et al. 2005; Tunved et al. 2006; Kulmala et al. 2013).

The emissions of BVOCs in the boreal forest arise through evaporation from specialized storage structures (Guenther et al. 1995) and from de novo biosynthesis (Ghirardo et al. 2010). Environmental factors, such as temperature and the amount of photosynthetic active radiation, govern the emissions, but environmental stress factors, such as drought and ozone exposure, may increase or decrease emissions. There is also considerable variation between individual trees in their BVOC emission fingerprints, which, in Scots pine, are composed of a variable mixture of alpha-pinene, beta-pinene, delta-carene, and sesquiterpenes (e.g., Hakola et al. 2006; Bäck et al. 2012). Additionally, new needle development and growth processes can be large sources of BVOCs (e.g., Aalto et al. 2015) associated with spring recovery of the ecosystem (Dal Maso et al. 2009). Approximately 80% of BVOC emissions in a conifer forest stand originate from trees, with the rest from the soil (Aaltonen et al. 2011), and both source strengths were measured with automated cuvettes during the BAECC campaign (Table 1).

The winter temperatures during the BAECC period were abnormally mild, with photosynthesis (net carbon uptake) persisting even in February, leading to increased emissions of BVOCs. This indicated that the potential for biogenic production of precursor gases was high during the spring months. Monoterpenes are the main emitted compound group from coniferous forests around Hyytiälä (Hakola et al. 2006). The shoot-scale enclosure measurements with proton transfer mass spectrometry revealed that, as in many previous years, extremely high emission rates in early spring coincided with the spring recovery period of trees during early–mid-March and that these peaks
provide 2–3 times higher monoterpene emissions compared to the rest of spring (Aalto et al. 2015). The maximum emission rates were observed during 11–12 March 2014, with another high-emission period seen during new foliage growth in late May–early June (Aalto et al. 2014). During summer, the highest emissions coincided with high temperatures in early and late summer, whereas the relatively cool weeks around midsummer resulted in lower monoterpene emissions. The emissions from the biosphere together with their oxidation products lead to new particle formation (Kulmala et al. 2004, 2013). This process provides a major source of particles in clean boreal forests (Fig. 2; Kulmala et al. 2001). Although many precursors (sulfuric acid, amines, and various organic vapors) have been attributed to initial gas-to-particle conversion, the dominant process growing these clusters to climatically relevant sizes is, without doubt, condensation of organic vapors (Kulmala et al. 1998; Riipinen et al. 2011; Zhou et al. 2014). This fact is also underlined by the typical chemical composition observed, which indicates that the majority of particulate mass in natural boreal forests is made up of organic compounds (Jimenez et al. 2009).

Aerosol formation occurred frequently during BAECC (Fig. 2). The concentration of nanoparticles was probed with a suite of scanning particle size magnifiers (PSM; Vanhanen et al. 2011) and the mobile versatile size-analyzing nuclei counter (vSANC; Pinterich et al. 2016) in the size range 1–5 nm at ground level and at 35-m height. Overall, the seasonal cycle of events during BAECC was typical for Hyytiälä with a maximum in spring and a secondary maximum in autumn. The separation of ion-induced and neutral pathways was determined

| Table 1. AMF2 and SMEAR2 measurements and time lines of the IOPs during BAECC. |
|--------------------------|-----------------------------------------------|
| AMF2 (Data available from ARM data archive: www.archive.arm.gov/armlogin/login.jsp; ARM 2015) | SMEAR II (Selected data available from SmartSMEAR portal: www.atm.helsinki.fi/smartSMEAR; Junninen et al. 2009) |
| Aerosol optical properties (nephelometer) | Aerosol number size distribution [1 nm–10 µm, particle size magnifier (PSM), differential mobility particle sizer (DMPS), neutral cluster and air ion spectrometer (NAIS), and aerodynamic particle sizer (APS)] |
| Aerosol number concentration > 10 nm [condensation particle counter (CPC)] | Aerosol number concentration (PSM, CPC) |
| Atmospheric profiling (radiosoundings) | Atmospheric ion distribution [AIS, balanced scanning mobility analyzer (BSMA)] |
| Thermodynamic state of the atmosphere | Aerosol optical properties (scattering, absorption, and extinction) |
| Wind speed and direction | Total and size resolved cloud condensation nuclei counter (CCNC) |
| Boundary layer height (ceilometer) | Aerosol vertical profile, boundary layer height, wind, and cloud-base height (HALO Photonics doppler lidar, Vaisala ceilometer) |
| Cloud-base height [ceilometer, micro pulse lidar (MPL)] | Aerosol volatility distribution [volatile differential mobility particle sizer (VDMPS); Häkkinen et al. 2012] |
| CCNC | Aerosol mass concentration (impactor sampling, on-line mass analyzer) |
| Cloud particle size distribution [X-band scanning ARM cloud radar (XSACR)] | Aerosol chemical composition [aerosol chemical speciation monitor (ACSM), Sunset EC/OC analyzer, monitor for aerosols and gases in ambient air (MARGA), filter sampling for off-line analysis] |
| Hydrometeor fall velocity (XSACR) | Trace gas concentrations and profiles (NO, NOx, O3, SO2, H2O, CO2, CO, COS, and VOC) |
| Hygroscopic growth [hygroscopic tandem differential mobility analyzer (HTDMA)] | Ecosystem-scale fluxes: latent, sensible heat, CO2, CH4, COS, CH3O, and aerosols |
| Liquid water path (LWP) | Biosphere–atmosphere exchange (VOC, CO2, H2O, NOx, and O3) from branch, soil, and stem trees |
| Ozone concentration | Chlorophyll fluorescence of pine needles |
| Profiles of aerosol backscatter, extinction and depolarization [high spectral resolution lidar (HSRL)] | Sap flow, stem properties, needle, and stem growth |
| Radar Doppler [marine W-band ARM cloud radar (MWACR), Ka-band zenith pointing radar (KAZR)] | Surface meteorology and profiles 2–127 m |
| Radar polarization (XSACR) | Solar radiation (global, ultraviolet A and B, photosynthetically active radiation, spectroradiometer, reflected, direct and diffuse, and up and down) |
| Radar reflectivity (XSACR, MWACR, KAZR) | Longwave radiation radiation (up/down) |
| Surface meteorology (ARM surface meteorological system) | Radon, radioactivity |
| Vertical velocity (KAZR) | |
through measurements of both ions and neutral particle concentrations, with the neutral pathway dominating formation rates. Figure 2 displays an example of a new particle formation event starting from sub-3-nm sizes during the morning hours of 23 April. During subsequent days, as the synoptic situation remained unchanged, these particles grew larger in size, leading to a factor of 10 increase in the concentration of CCN-sized particles. Typically, higher concentrations of precursor vapors enhance aerosol growth (Kulmala et al. 2001; Riipinen et al. 2012). There are indications that some of the organic molecules are also relevant for the initial steps of aerosol formation (Riccobono et al. 2014; Schobesberger et al. 2013a; Kirkby et al. 2016; Tröstl et al. 2016). During BAEC spring IOP (Table 1).

Based on a Filter Inlet for Gases and Aerosols chemical-ionization mass spectrometer (FIGAERO-CIMS

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The history of the Hyytiälä forestry field station goes back over 100 years. The University of Helsinki founded the station to enable forestry teaching and research in field conditions in 1910. Atmospheric research has been part of Hyytiälä station since the mid-1980s as a result of an interdisciplinary Finnish Acidification Research Programme (HAPRO; Kauppi et al. 1990) and because of the Chernobyl nuclear power plant accident in April 1986 as Hyytiälä was in the area of the radioactive fallout (Raunemaa et al. 1987; Nygren et al. 1994). These events paved the road to establishing a continuous, comprehensive measurement station dedicated to forest–atmosphere interactions. In 1995, the operational phase of SMEAR II (Hari and Kulmala 2005) was started. After 20 years of measurements and incessant development, SMEAR II features the most comprehensive atmospheric observations with the longest continuous time series, for example, on submicron aerosol number size distributions.

One of the key findings of SMEAR II has been that secondary aerosol formation from gas-phase precursors is a frequent phenomenon in the boreal environment (Mäkelä et al. 1997; see Fig. 2 for an example from the BAECC campaign), occurring on average every fourth day. This process is most active during spring, when on almost half of the days we observe the appearance of sub-3-nm aerosol particles and their subsequent growth (Dai Maso et al. 2005). A secondary maximum of the events takes place in autumn. A typical source strength associated with the events is 1 cm$^{-2}$ s$^{-1}$ with growth rates varying from 0.5 to 8 nm h$^{-1}$ (Kulmala et al. 2004). As this process takes place in a clean environment, this relatively small source, occurring over a large area, is able to produce particles large enough to activate as cloud droplets (Kerminen et al. 2012) and contribute up to 60% of the CCN-sized particles in the region (Merikanto et al. 2009).

Once the events were discovered, the quest to find the precursor vapors, their concentrations, and detailed mechanism commenced. The pathway is dominated by neutral nucleation, and the role of ions is limited (Kulmala et al. 2007). Laboratory experiments have identified several key vapors contributing to the initial steps of aerosol formation, such as sulfuric acid (Sipilä et al. 2010), ammonia (e.g., Kirkby et al. 2011), amines (Petäjä et al. 2011; Almeida et al. 2013), and organics (Riccobono et al. 2014; Tröstl et al. 2016). All of these compounds can enhance cluster stability and initial growth and therefore contribute to the process (Kulmala et al. 2013). In continental locations, such as Hyytiälä, sulfuric acid has been identified as a crucial ingredient (Weber et al. 1995; Petäjä et al. 2009), but its concentration is not high enough to explain further growth to climatically relevant particle sizes (Kulmala et al. 1998). In the boreal environment, the role of organic vapors in the growth is important (Riipinen et al. 2012), supported by the dominance of organics in the bulk chemical composition (Jimenez et al. 2009). A very plausible candidate for the vapor responsible for the aerosol growth to CCN sizes is a group of compounds called ELVOCs that readily participates both in the early stages of clustering and the growth (Ehn et al. 2014).

The modern high-resolution mass spectrometry (e.g., Ehn et al. 2010; Smith et al. 2010; Jokinen et al. 2012; Lopez-Hilfiker et al. 2014) together with the capacity to perform physical characterization of nanoparticles below 3 nm in size (Kulmala et al. 2007, 2013b) has led to breakthroughs in understanding the initial steps of aerosol formation in the boreal environment as well as in their subsequent growth to CCN sizes (Kerminen et al. 2012). The next stage of research requires the combination of measurements (in situ and active remote sensing) and multi-scale modeling tools (quantum chemical modeling, process-level modeling, and regional and global models) to resolve the vertical and spatial variability of the processes affecting aerosol–cloud–climate interactions.

One of the key findings of SMEAR II has been that secondary aerosol formation from gas-phase precursors is a frequent phenomenon in the boreal environment (Mäkelä et al. 1997; see Fig. 2 for an example from the BAECC campaign), occurring on average every fourth day. This process is most active during spring, when on almost half of the days we observe the appearance of sub-3-nm aerosol particles and their subsequent growth (Dai Maso et al. 2005). A secondary maximum of the events takes place in autumn. A typical source strength associated with the events is 1 cm$^{-2}$ s$^{-1}$ with growth rates varying from 0.5 to 8 nm h$^{-1}$ (Kulmala et al. 2004). As this process takes place in a clean environment, this relatively small source, occurring over a large area, is able to produce particles large enough to activate as cloud droplets (Kerminen et al. 2012) and contribute up to 60% of the CCN-sized particles in the region (Merikanto et al. 2009).

Once the events were discovered, the quest to find the precursor vapors, their concentrations, and detailed mechanism commenced. The pathway is dominated by neutral nucleation, and the role of ions is limited (Kulmala et al. 2007). Laboratory experiments have identified several key vapors contributing to the initial steps of aerosol formation, such as sulfuric acid (Sipilä et al. 2010), ammonia (e.g., Kirkby et al. 2011), amines (Petäjä et al. 2011; Almeida et al. 2013), and organics (Riccobono et al. 2014; Tröstl et al. 2016). All of these compounds can enhance cluster stability and initial growth and therefore contribute to the process (Kulmala et al. 2013). In continental locations, such as Hyytiälä, sulfuric acid has been identified as a crucial ingredient (Weber et al. 1995; Petäjä et al. 2009), but its concentration is not high enough to explain further growth to climatically relevant particle sizes (Kulmala et al. 1998). In the boreal environment, the role of organic vapors in the growth is important (Riipinen et al. 2012), supported by the dominance of organics in the bulk chemical composition (Jimenez et al. 2009). A very plausible candidate for the vapor responsible for the aerosol growth to CCN sizes is a group of compounds called ELVOCs that readily participates both in the early stages of clustering and the growth (Ehn et al. 2014).

The modern high-resolution mass spectrometry (e.g., Ehn et al. 2010; Smith et al. 2010; Jokinen et al. 2012; Lopez-Hilfiker et al. 2014) together with the capacity to perform physical characterization of nanoparticles below 3 nm in size (Kulmala et al. 2007, 2013b) has led to breakthroughs in understanding the initial steps of aerosol formation in the boreal environment as well as in their subsequent growth to CCN sizes (Kerminen et al. 2012). The next stage of research requires the combination of measurements (in situ and active remote sensing) and multi-scale modeling tools (quantum chemical modeling, process-level modeling, and regional and global models) to resolve the vertical and spatial variability of the processes affecting aerosol–cloud–climate interactions.
chemical composition were performed using an Aerosol Chemical Speciation Monitor (ACSM, Aerodyne Research Inc.; Ng et al. 2011). Data coverage during the BAEGC campaign was extensive, with a good dataset obtained for studying the seasonality of the aerosol-phase composition. Increased organic contributions during the most photosynthetically active seasons was clearly observed, whereas in wintertime, anthropogenic sulfate reached its maximum, composing up to 25% of the nonrefractory submicron mass.

**EXTENDING SURFACE MEASUREMENTS INTO THE VERTICAL.** Based on direct observations inside clouds, Kerminen et al. (2005) showed that secondary aerosols formed from biogenic emissions can be activated to become cloud droplets. However, unraveling the mechanisms by which biogenic aerosol interacts with clouds requires that the vertical profile of aerosol, clouds, and turbulence be fully characterized in tandem. The process can be split into two main steps: the transport of biogenic aerosol from the surface into the boundary layer and free troposphere and the participation in cloud formation.

The vertical profile of aerosol above the SMEAR II site was studied extensively through the use of remote sensing by lidar and by in situ aircraft-based measurements during three flight IOPs. Continuous remotely sensed vertical profiles of aerosol were obtained from a multitude of lidar instruments. These operated quasi continuously throughout the entire campaign period. For the instrumentation and timing of IOPs, the reader is referred to Table 1.

The transport of biogenic aerosol from the surface into the boundary layer is driven by turbulent mixing. This mixing ensures that all air within the turbulent layer is in intermittent contact with the surface, on time scales from 10 to 30 minutes, with the top of this layer termed the mixing-layer height (MLH; e.g., Emeis et al. 2008). The MLH can be defined in terms of the turbulent kinetic energy dissipation rate (Barlow et al. 2011), determined directly from the high-resolution vertically pointing (O’Connor et al. 2010) and scanning (Vakkari et al. 2015) Doppler lidar data provided by FMI at Hyytiälä. The potential for aerosol-layer identification and aerosol typing through a combination of backscatter coefficient and circular depolarization ratio is clearly shown in Figs. 3 and 4. Humid boundary layers, dry elevated layers, and humid elevated
layers can all be distinguished in high-spectral-resolution lidar (HSRL) data.

The flight IOPs took place in three seasons: early spring, beginning of summer, and beginning of autumn. The University of Helsinki (UHEL) operated a Cessna FR172F single-engine light aircraft modified to carry aerosol instrumentation as described in Schobesberger et al. (2013b). Figure 3 shows simultaneous measurements with Cessna and ARM HSRL on 2 April 2014. The flight path for this particular day is typical of the route selected during the flight campaigns. It is oriented in the south–north direction and consists of an initial ascent up to 3.5 km and then several legs at different altitudes above and within the boundary layer. In total, 144 flight hours were flown during 33 days with the Cessna, and all flights were in the vicinity of the SMEAR II station. During the flight IOP at the beginning of autumn, FMI operated a Short SC.7 Skyvan, an unpressurized aircraft (Short Brothers and Harland Ltd., Northern Ireland, United Kingdom) owned by Aalto University. Inclusion of chemical composition profiles from Skyvan flights (Fig. 4) permits the correct choice of refractive index when deriving microphysical properties from the lidar profiles. The details of the instrumentation in both aircraft are presented in Table 1.

The microphysical retrievals can be improved through harnessing data from the multiwavelength Raman lidar system PollyXT (Althausen et al. 2009; Engelmann et al. 2016), where available, through collaboration with the European Aerosol Research Lidar Network (EARLINET; Pappalardo et al. 2014), now within ACTRIS. The combination of multiple channels through the use of the “3 backscatter + 2 extinction + 1 depolarization” approach allows aerosol typing (e.g., Mona et al. 2012; Mattis et al. 2004) and the retrieval of aerosol microphysical optical properties through the application of specific inversion algorithms (Müller et al. 1999; Veselovskii et al. 2005). The retrievals have been demonstrated to have the unique ability of providing range-resolved aerosol effective radius and a complex refractive index (e.g., Müller et al. 2007). The addition of sun photometer observations may permit the determination of the aerosol mass concentration profile, including separation of the fine and course components (Chaikovsky et al. 2016; Lopatin et al. 2013; Binietoglou et al. 2015). The range-resolved properties (e.g., aerosol size distribution, refractive index, single-scattering albedo, mass concentration, and water vapor) can then be independently verified at the surface and from the aircraft. The impact of humidity on aerosol depolarization ratios retrieved from lidar can also be examined in detail, with Fig. 4 showing how closely these two parameters can be linked (low depolarization values imply spherical hygroscopic aerosol, high depolarization values imply dry nonspherical aerosol).

Fig. 3. UHEL Cessna (a) flight track and (c) altitude track during an aircraft IOP centered on Hyytiälä on 2 Apr 2014. The color of the track provides the total aerosol number concentration. (b) ARM backscatter coefficient and (d) circular depolarization ratio data for the same day, showing the potential for aerosol-layer identification and aerosol typing. Aircraft data from three IOPs (a total of 144 flight hours during 33 days with the UHEL Cessna) provide essential validation of remote sensing techniques.
Such a dataset will help identify the relative impact of long-range transport of material and local sources, and we will also investigate the mechanisms for dispersion. Besides confirming the remote sensing methods, the in situ data obtained by the aircraft can be used either as input or validating data for different atmospheric models, such as the model to simulate the concentrations of organic vapors, sulfuric acid, and aerosols (SOSAA; Boy et al. 2011). The inclusion of chemical composition (Fig. 4) and Picarro trace gas profiles from Skyvan provides a direct measurement of the impact of the environment on the aerosol properties during their transport from the surface into the boundary layer.

CLOUD VERTICAL PROFILING. Well-established ARM and Cloudnet (Illingworth et al. 2007) algorithms were used to derive vertical profiles of cloud properties for the entire campaign. The vertical profile of cloud macrophysical properties, including layer boundaries and phase, was obtained from a combination of vertically pointing Doppler cloud radar [Ka-band ARM zenith radar (KAZR) or marine W-band ARM cloud radar (MW ACR) when KAZR is unavailable] and lidar (HSRL and ceilometer), following Illingworth et al. (2007). Combinations of various radar wavelengths (including scanning instruments operating at vertical) together with lidars and microwave radiometers were then used to retrieve the cloud microphysical properties, such as water content and flux, size distributions, and ice morphology. Drizzle properties, including median equivolumetric size, number concentration, drizzle liquid water content, and drizzle liquid water flux, were derived using a combination of KAZR (or MWACR) and a ceilometer (O’Connor et al. 2005).

Investigating the influence of biogenic aerosols on clouds requires that both the aerosol and cloud properties can be measured reliably and within the same volume. This poses a challenge since it is difficult to measure aerosol properties within the cloud by remote sensing methods. However, when considering liquid clouds coupled with the boundary layer, it is safe to assume that the vertical column within and below cloud is well mixed, producing well-defined profiles and gradients of atmospheric properties. In a well-mixed column, in-cloud properties can then be related to below-cloud aerosol properties and, in principle, to aerosol properties (such as size distribution, chemical composition, and hygroscopicity).

Fig. 4. (left) FMI Skyvan measurements during an aircraft IOP centered on Hyytiälä on 4 Sep 2014, showing (a) aerosol and CCN number concentration and (b) aerosol composition from Aerodyne aerosol mass spectrometer (AMS) for the first ascent leg (1340–1415 UTC). Data have been averaged to 50-m-height intervals, with thick lines displaying the mean values and thin horizontal lines indicating plus or minus one standard deviation. (right) Time–height sections of ground-based ARM HSRL (c) backscatter coefficient and (d) circular depolarization ratio data for the same day, showing the potential for aerosol-layer identification and aerosol typing. Superimposed on the HSRL plots is the Skyvan altitude track; the monochrome color of the track provides the total aerosol number concentration in (c) and the water vapor mixing ratio from Picarro in (d).
The snowfall measurement experiment (BAECC SNEX; Fig. SB1) was a collaborative effort between DOE ARM, University of Helsinki, FMI, NASA, and Colorado State University. The IOP took place from 1 February to 30 April 2014 and was dedicated to documenting snowfall microphysics through a combination of multi-frequency (C, X, Ka, and W band) radar, microwave radiometer, and lidar measurements supplemented by a comprehensive suite of surface-based precipitation observations. Combining the multi-instrumental remote sensing and ground-based observations provides a detailed view of snow growth processes, such as condensation growth of ice crystals, aggregation, and riming.

The standard AMF2 surface-based precipitation measurement instruments were supplemented by an array of sensors, given in Table SB1. The operational schedule of the nearest FMI dual-polarization weather radar was modified to include range–height indicator (RHI) scans above the AMF2 location.

To facilitate accurate surface measurements of snowfall properties, a DFIR wind protection (shown in Fig. SB1) for the following instruments was built on site: weighing precipitation gauge, laser disdrometer (OTT Parsivel), and 2D video disdrometer. Because of the duplication of the instruments, consistency of the precipitation microphysics retrievals can be checked and the dataset can also be used to characterize snowfall measurement errors as a function of wind speed. The wind measurements were performed at instrument height inside and outside of the fence and at 10-m height.

During the IOP, more than 20 precipitation events were recorded, with conditions varying from dry to wet snow and particle types ranging from pristine crystals to densely rimed particles and fluffy aggregates.

### Table SB1. List of BAECC SNEX instruments.

<table>
<thead>
<tr>
<th>Instrument name</th>
<th>Inside DFIR</th>
<th>Outside DFIR</th>
<th>Measured quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighing gauge (OTT Pluvio²)</td>
<td>×</td>
<td>×</td>
<td>Precipitation rate and accumulation</td>
</tr>
<tr>
<td>2D video disdrometer</td>
<td>×</td>
<td>×</td>
<td>PSD, fall velocity, and shape</td>
</tr>
<tr>
<td>Video disdrometer (OTT Parsivel)</td>
<td>×</td>
<td>×</td>
<td>PSD, fall velocity</td>
</tr>
<tr>
<td>3D anemometer (METEK and Gill)</td>
<td>×</td>
<td>×</td>
<td>3D wind field</td>
</tr>
<tr>
<td>Total precipitation sensor (Yankee TPS-3100)</td>
<td>×</td>
<td>—</td>
<td>Precipitation rate and accumulation</td>
</tr>
<tr>
<td>Particle Imaging Package (NASA)</td>
<td>—</td>
<td>×</td>
<td>PSD, fall velocity, fall attitude, and shape of particles</td>
</tr>
<tr>
<td>Micro Rain Radar (METEK)</td>
<td>—</td>
<td>×</td>
<td>Radar reflectivity and Doppler velocity (60–1000 m)</td>
</tr>
<tr>
<td>Snow depth sensor (Jenoptik SHM-30)</td>
<td>—</td>
<td>×</td>
<td>Snow depth</td>
</tr>
</tbody>
</table>
measured at the surface. Figures 3 and 4 both show suitable clouds at the top of the boundary layer that are coupled to the surface (in Fig. 3, suitable clouds are at 1.5–2 km in altitude from 1000 UTC to just after 1200 UTC; in Fig. 4, the intermittent clouds are present all day between 1 and 1.5 km). Liquid clouds in the boundary layer will be classified according to their aerosol source, biogenic, background, or other aerosol source, once these data are available and stratified by their macro- and microphysical properties to document evidence for the influence of biogenic aerosols on clouds.

**CLOUDS TO PRECIPITATION.** In Finland, a high-latitude country, the majority of precipitation is initiated by ice-phase processes (Mason 1971). Since

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**Fig. 5.** KAZR observations of (a) reflectivity factor and (b) Doppler velocity, (c) MWR measurements of liquid water path (LWP), (d) particle size distribution by PIP, and (e) retrieved bulk density values. The bulk densities of snow were retrieved by applying the method of Böhm (1989) to 2D video observations and from a combination of PIP and gauge observations.
By combining the detailed observations obtained during BAECC with a range of numerical models, we ultimately aim to understand the role of biogenic aerosols in cloud formation and microphysical processes leading to precipitation. Here, one example is presented in which surface and remote sensing observations are combined with a numerical simulation conducted with the WRF Model, version 3.6.1 (Skamarock et al. 2008).

During BAECC SNEX (see “Clouds to precipitation” section and the “BAECC SNEX” sidebar), six cases of layered cloud that resulted in enhanced surface precipitation occurred. On 21–22 February, a frontal system that led to multiple cloud layers and snowfall moved east across Finland. This case is analyzed in detail using WRF Model output and observations (some of which are presented in Fig. 5) to determine 1) what microphysical processes are occurring aloft and how these relate to the type and intensity of precipitation observed at the surface and 2) how accurately multiple mixed-phase cloud layers and their microphysical processes are represented by WRF.

The WRF simulation was initialized from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) data (Dee et al. 2011) at 1200 UTC 20 February 2014 and run for 72 h. The simulation domain consisted of an outer domain with 30-km grid spacing covering most of northern Europe and an inner nested domain with 10-km grid spacing covering Finland and neighboring sea areas. Boundary layer turbulence was parameterized using the Yonsei University (YSU) scheme, deep convection was parameterized using the Kain–Fritsch scheme, and the Morrison double-moment six-class scheme was used to parameterize the microphysics. The WRF simulation did not capture the thin layer of boundary layer cloud that was present before the arrival of the front, which is, in part, due to model spinup issues, but in general such low-level clouds are poorly represented in numerical weather prediction (NWP) and climate models (Stevens et al. 2007). Associated with the frontal passage were two cloud layers, both of which were captured well by WRF (Figs. SB2 and 5).

The observed radar reflectivity (Fig. 5a) shows that between 2300 and 0000 UTC, precipitation from the upper-cloud layer falls into the lower-cloud layer. The same feature is present in the WRF simulation; however, it occurs 1.5 h later, between 0030 and 0130 UTC.

**Fig. SB2.** Hydrometeor properties as simulated by WRF between 0600 UTC 21 Feb and 0600 UTC 22 Feb 2014 at the grid point closest to Hyytiälä. (a) Number concentration (m$^{-3}$) of ice particles, (b) number concentration (m$^{-3}$) of snow particles, and (c) the sum of the rain and cloud mixing ratios (kg m$^{-3}$). The solid lines indicate temperature contours: solid black is −40°C, dashed black is −15°C, blue is −8°C, and white is −3°C.
0300 UTC (Fig. SB2). At the upper levels, where the temperature is below −40°C, there are large numbers of ice particles (Fig. SB2). These primary ice and snow particles produced in the upper-level seeder cloud fall into the lower feeder cloud and grow by accretion. Observations and model simulations of liquid and ice water path (Fig. SB3) support this as almost all liquid water is removed with the onset of the precipitation falling from the upper cloud into the lower cloud and there is an increase in ice water path (at 2300 UTC in the observations and 0030 UTC in the model simulation). In addition, new ice is generated at the top of the seeder cloud (at temperatures from −20°C to −15°C) and hence would be plates or dendrites. This results in two distinct populations that have different fall speeds and therefore aggregation can readily occur. Observations (Fig. 5) show that after 2300 UTC, there are more large particles and that the bulk density of snow at the surface decreases, indicative of aggregates. Thus, it can be concluded that a seeder–feeder mechanism occurs and alters the properties of the surface precipitation.

Also of interest in this case is the high concentration of ice particles simulated by WRF between 1930 and 2130 UTC at temperatures between −8°C and −3°C, the temperature range where the Hallett–Mossop ice splintering processes is expected to occur (Hallett and Mossop 1974). However, in this case it is unlikely that this ice is produced by this process as there is little or no supercooled liquid present. This potential case of secondary ice production, and others observed during BAECC SNEX, will be the topic of future studies.

Overall, WRF reproduces the bulk aspects of this frontal case very well. There is reasonable agreement in the cumulative precipitation when the entire frontal system is considered, yet WRF simulates the precipitation to be lighter and to occur over a longer period of time than what was observed (Fig. SB3). Furthermore, notable discrepancies between the measured and simulated number concentration of ice/snow particles at the surface were detected (Fig. SB3) as WRF was not able to capture the increase in frozen hydrometeor number that occurred between 2300 and 0000 UTC. This highlights the challenges models face in correctly simulating precipitation amounts and properties of hydrometeors and indicates that microphysical processes are not yet adequately represented in numerical weather prediction or climate models.

**Fig. SB3.** Observed (red lines) and WRF-simulated (blue lines) (a) ice water path (IWP) and (b) LWP. In WRF, LWP was calculated from the vertical integral of the sum of the cloud and rain mixing ratios, and IWP was calculated as the vertical integral of the sum of the snow, ice, and graupel mixing ratios. (c) Accumulated surface precipitation at Hyytiälä from observations (red) and WRF simulation (blue). (d) Observed total number concentration of solid precipitation particles at the surface (red), WRF-simulated total number concentration of frozen hydrometeors [snow, ice, and graupel (blue)], and WRF-simulated total number concentration [snow, ice, graupel, and rain (black)] at the lowest model level (approximately 25 m).
part of the BAECC campaign took place during winter, surface-based observations of solid precipitation microphysics, that is, particle size distribution, particle habit, and their physical properties, can be used to infer what cloud-to-precipitation processes take place and guide retrievals based on remote sensing observations. To take advantage of this opportunity, an intensive observation period termed the BAECC Snowfall Experiment (SNEX), focusing on snowfall, was undertaken from 1 February through to 30 April 2014.

During this IOP, more than 20 snowfall events were recorded. During these events, the dual-channel microwave radiometer detected the presence of liquid water more than 80% of the time. Given the presence of supercooled liquid in the majority of the cases, the focus of the IOP was to investigate how remote sensing observations, that is, multifrequency and dual-polarization Doppler radar in combination with lidar and microwave radiometer, can be used to identify ice-phase precipitation processes, namely, the Bergeron process, riming, aggregation, and ice multiplication, and study their evolution. Because a transition from one process to another could happen within a precipitation event, our analysis and data collection strategies were selected to allow investigation of how the environmental conditions influence these transitions, even if they happen on time scales as short as a few minutes.

Accurate and consistent quantitative observations of snow are notoriously challenging (Rasmussen et al. 2012). To ensure the quality of the measurements and to obtain an estimate of uncertainty of retrieved microphysical properties, a comprehensive precipitation measurement setup was established (see sidebar on "BAECC SNEX" for more information). The observations of precipitation intensity and particle size distributions, particle fall velocities and sizes, particle dimensions and shapes in combination with retrievals of snow bulk density, and mass–dimensional relations can be used for classification and characterization of precipitating ice particles and inferences of prevailing precipitation processes. These observations and retrievals were carried out in coordination with radar observations to link surface observations of precipitation microphysics to vertical profiles of meteorological products, as, for example, shown in Kneifel et al. (2015). An example of this analysis applied to a precipitation event that took place on 21 February 2014 is shown in Fig. 5. Furthermore, in the sidebar “Modeling activities for investigating aerosol transport, source attribution, and cloud-to-precipitation processes,” an example of how a numerical model—the Weather Research and Forecasting (WRF) Model—can be used to further understand how microphysical processes occurring in a vertical column affect the properties of precipitation at the surface is presented.

During BAECC SNEX, surface precipitation observations were performed by a number of instruments. Given the duplication of most of the precipitation instruments and utilization of instruments with different measurement principles, the consistency of the retrieved snow microphysical properties can be checked. For example, precipitation intensity is measured by two weighing gauges [inside and outside of the Double Fence Intercomparison Reference (DFIR)] and by a total precipitation sensor (Hotplate). Those instruments supplement standard AMF instrumentation. Particle size distributions were recorded by two OTT Parsivel laser disdrometers, two 2D video disdrometers, and a particle imaging package (PIP) designed by the National Aeronautics and Space Administration (NASA), which is the new generation of snow video imager, providing also images of individual hydrometeors (Newman et al. 2009).

Similarly, retrieval techniques that rely on different sets of assumptions were adopted. To characterize precipitating ice particles, bulk density of falling snow, velocity–dimensional (v–D) relations, areal ratios, and mass–dimensional (m–D) relations must be derived. The bulk density can, for example, be estimated using several methods:

- by matching 2D video and/or PIP-based estimates of snowfall rate to the value recorded by the gauges, similar to the techniques described by Brandes et al. (2007);
- estimating the bulk density of freshly fallen snow by comparing changes in snow depth to the precipitation accumulation (Power et al. 1964); and
- by matching reflectivity values calculated from PSD observations with directly observed reflectivity values (Huang et al. 2010).

An example of retrieved bulk density values from PIP and weighing-gauge measurements is shown in Fig. 5. By combining observed particle area ratios and v–D relations, the mass–dimensional relations were estimated by following the procedure described by Böhm (1989) and Huang et al. (2015); see Fig. 5 for the bulk density calculated from the retrieved m–D relation. As one can see from Fig. 5, the bulk densities retrieved using two different sets of instruments and methods match rather well, which supports our confidence that such retrievals are possible and meaningful.
SUMMARY AND OUTLOOK. During BAECC, the physical, chemical, and optical characterization of aerosol particles at the surface was conducted simultaneously with comprehensive cloud and precipitation observations. This was enabled by combining the state-of-the-art capabilities of both the SMEAR II research station at Hyytiälä, Finland, and the AMF2, a mobile research facility, which was brought to Hyytiälä by the ARM Program of the U.S. Department of Energy. This facilitated good opportunities to benefit from the NASA Global Precipitation Measurement (GPM) mission ground validation in surface particle size distribution and water equivalent rate gauges, while the European Commission via ACTRIS transnational access provided resources for gap-filling aerosol physical and chemical measurements as well as cloud observations.

Overall, the BAECC campaign was highly successful and provided a vast 8-month-long dataset obtained during three seasons, including a variety of cloud and precipitation systems. Together with the extensive flight campaigns, and with the comprehensive near-20-yr-long continuous surface-based measurements of aerosols at SMEAR II, the representativeness of the BAECC dataset can be thoroughly evaluated.

The connection between increased aerosol concentration of aerosol particles and cloud properties has not yet been properly quantified because of the challenges connecting in situ aerosol measurements at the ground and cloud properties aloft (e.g., Paasonen et al. 2013; Kulmala et al. 2014). With vertical profile measurements during BAECC and suitable modeling tools, the quantification of these connections can now be undertaken. The comprehensive observations available in BAECC enable radiative transfer modeling to estimate the effects of aerosols and clouds on the radiative (e.g., Zieger et al. 2015) energy balance of the entire atmospheric column. With the combination of the measurements obtained during BAECC and the supporting SMEAR network, combined with satellite data, we will be able to evaluate these correlations on a larger spatial scale in the boreal environment.

Expansion of the pointwise measurements to a larger context with satellite-derived data is ongoing (Sporre et al. 2016; Krüger et al. 2016, manuscript submitted to J. Geophys. Res.). The data will enable development of proxy variables that can be expanded into a global perspective (e.g., Kulmala et al. 2011).

The comprehensive data will be utilized in multiscale modeling. For example, the atmosphere column model SOSAA (Boy et al. 2011), combining different emission modules, boundary layer dynamics, and both chemical and aerosol dynamical processes, will be used to investigate the formation, vertical transport, and aging of atmospheric aerosols inside the mixing layer. The model simulations will link our knowledge based on long-term ground observation with the new measurements by the AMF instruments. Valuable sensitivity studies with the Weather Research and Forecasting Model with Chemistry (WRF-Chemistry) with different cloud microphysics parameterizations are possible where the models can be verified against multifrequency radar observations available from AMF2.

Future work will take full advantage of the success of the BAECC campaign and contribute toward the following objectives: 1) to study the interactions between aerosol microphysics and turbulent mixing within the continental boundary layer to understand the transformation of aerosol while being transported from the surface to clouds, 2) to evaluate the impacts of long-range transport and transformation of aerosol on how they can act as CCN, 3) through comprehensive aerosol typing with the various observation methods to determine the roles of the regional and long-range transported aerosol in the formation of CCN-sized particles, 4) to investigate the sensitivity of evolving cloud–precipitation processes on CCN concentrations, 5) to characterize aerosol removal and transformation mechanisms as a function of particle size and precipitation type, and 6) to compare and understand falling-snow precipitation processes and rates to remote sensing retrievals from satellite missions such as GPM.

Finally, the representativeness of the BAECC data will be understood within a long-term perspective through connection to the nearly 20-yr continuous measurement dataset at SMEAR II, unique globally in the sense that nowhere else has comparable measurements that have been performed continuously for such a long time period.

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REFERENCES


**Adaptive Governance and Climate Change**

Ronald D. Brunner and Amanda H. Lynch

As greenhouse gas emissions and temperatures at the poles continue to rise, so do damages from extreme weather events affecting countless lives. Meanwhile, ambitious international efforts to cut emissions have proved to be politically ineffective or infeasible. There is hope, however, in adaptive governance—an approach that has succeeded in some communities and can be undertaken by others around the globe.

In this book:

- A political and historical analysis of climate change policy
- How adaptive governance works on the ground
- Why local, bottom-up approaches should complement global-scale negotiations
FOSTERING A COLLABORATIVE ATMOSPHERIC CHEMISTRY RESEARCH COMMUNITY IN THE LATIN AMERICA AND CARIBBEAN REGION

by Marcos Andrade-Flores, Nestor Rojas, Megan L. Melamed, Olga L. Mayol-Bracero, Michel Gruetter, Laura Dawidowski, Juan Carlos Antuña-Marrero, Carlos Rudamas, Laura Gallardo, Ruben Mamani-Paco, Maria de Fatima Andrade, and Nicolas Huneeus

A more cohesive and sustained community of atmospheric scientists is needed in the Latin America–Caribbean region to address the pressing issues of air quality and climate change.

The Latin America–Caribbean (LAC) region is defined as the countries south of the Rio Grande along the U.S.–Mexico border and includes Mexico, Central America, the islands of the Caribbean, and South America. Oftentimes, the LAC region is referred to as a homogeneous entity because of a common history, culture, and socioeconomic issues. However, to understand atmospheric chemistry in the region and its impacts on human health, ecosystems, and climate, it is of the utmost importance to address the heterogeneity of the LAC region’s physical and human geography (Fig. 1, left). For example, the climate of northern Mexico is hot and dry, while the climates of many Central America and Caribbean countries consist of a prolonged wet summer season that includes many tropical storms and hurricanes. Within South America the topography and climate vary greatly from the Andean regions to Amazonia and from Atlantic forests to Patagonia.

The LAC region is also unique in the fact that ~80% of the population lives in urban areas, resulting in high-density hot spots of urbanization and vast rural, sparsely populated areas (Heilig 2012; United Nations 2012) (Fig. 1, right). As a result of the high percentage of people living in urban areas and the coinciding emissions resulting from rapid development, urban air pollution has become a ubiquitous problem throughout the LAC region. Socioeconomic gradients among countries and inequities within them act as amplifiers of environmental problems, leading to differentiated emission patterns, exposure to air pollution, and vulnerability to climate change in urban areas (Bell et al. 2011; Gallardo et al. 2012; Mena-Carrasco et al. 2012; Romero-Lankao et al. 2013). Despite continuous growth in the number of stations monitoring air pollutants throughout the region and the development of policies to meet air quality standards, urban areas continue to exceed the World Health Organization’s (WHO) Air Quality Guidelines (WHO 2005; see Fig. 2). In addition, long-range transport of air pollutants can hinder local or national-level strategies to meet air quality standards.
standards in urban areas and can also decrease air quality in rural areas (CEC 1997; Galanter et al. 2000; Longo et al. 2009; NRC 2009; Zhu et al. 2012; Prospero et al. 2014).

Although atmospheric chemistry research has been conducted throughout the LAC region for decades, the amount and quality of the research vary greatly, as does the participation of local scientists. U.S. and European scientists often collaborate with local scientists where the research is being conducted, but very rarely is the invitation to work on such joint projects extended to other researchers in the LAC region. However, the uniqueness of the LAC region and the scientific questions that need to be addressed would greatly benefit from a cohesive community of scientists in the LAC region working together, and with international partners, to address atmospheric composition, its temporal evolution, and its impacts on human health, climate, and ecosystems.

In response to this need, members of the international Commission on Atmospheric Chemistry and Global Pollution (iCACGP) and the International Global Atmospheric Chemistry (IGAC) Project from the LAC region came together in 2013 to form the iCACGP/IGAC Americas Working Groups (AWG). The AWG aims to build a strong cohesive community and foster the next generation of atmospheric scientists within the region with the goal of contributing to the development of a scientific community focused on building collective knowledge for the Americas. The AWG aims to achieve this goal by focusing on four areas:

Fig. 1. (left) Land cover map and (right) population density of the LAC region.
• improving the collaboration and communication among scientists in the LAC region,
• connecting scientists within the LAC region to the international community,
• training and fostering the next generation of scientists in the LAC region, and
• enhancing the visibility and credibility of scientists in the LAC region.

Currently, the AWG consists of 12 members, including two cochairs, with the following composition: two scientists from Central America, two scientists from the Caribbean, three scientists from “Andean” countries (Bolivia, Ecuador, Venezuela, Peru, and Colombia), two scientists from “South American” countries (Argentina, Chile, Uruguay, and Paraguay), one scientist from Mexico, one scientist from Brazil, and one scientist from the United States or Canada. Each member serves a four-year term on the AWG and is to represent his/her country/subregion during their membership. The representation on the AWG was determined by the current scientific capacity of the different countries/subregions and is subject to change as scientific capacity grows in the LAC region.

The AWG has already been successful during its short two years of existence in achieving its goals by focusing on the four areas listed above. For example, in 2015 two short courses have been developed to train and foster the next generation of scientists. The first of these courses took place in La Paz, Bolivia, in July 2015 and was focused on aerosol measurements. The second course was focused on remote sensing techniques and took place in Mexico City, Mexico, in December 2015. These courses were organized by LAC region scientists, in collaboration with European and U.S. scientists as instructors. In an effort to connect LAC scientists to the international community and to enhance the visibility and credibility of scientists in the region, the AWG connected the Coalition for Clean Air and Climate (CCAC) with local scientists to have them lead and be contributing authors on a soon to be released assessment on short-lived climate pollutants (SLCPs) in the LAC region. Collaborations and communication between scientists in the LAC region have also been fostered by the AWG through the development of the Global Emissions Initiative (GEIA) Americas Working Group; coordinated efforts to install a World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) station, along with remote sensing instruments at the Smithsonian Tropical Research Institute in Panama; and an effort to create an Aerosol Robotic Network (AeroNet) observation network in the LAC region as well as the Caribbean Aerosol Network.

The iCACGP/IGAC AWG will continue to build upon current efforts in the LAC region to address research questions on atmospheric chemistry that impact human health, ecosystems, and climate. Here, we discuss current examples of research in the LAC region and identify remaining main scientific questions to be addressed and the key steps forward to address these questions through a collaborative atmospheric chemistry research community.

EXAMPLES OF ATMOSPHERIC RESEARCH IN LAC. Atmospheric chemistry research capabilities and achievements vary greatly among and even within LAC countries owing to the inherent characteristics of the research systems and the criticality of the issues related to atmospheric chemistry in every country. Urban air pollution in Mexico City, for instance, triggered the cultivation of scientists, research groups, institutes, and large projects that have increased the level of knowledge and helped decision-makers to address air pollution. In Brazil research policies have produced a robust scientific system that has increased

![Fig. 2. The PM$_{10}$ and PM$_{2.5}$ annual average levels in some LAC cities, based on official 2010–13 data, according to availability for each city (WHO 2014b).](image-url)
scientific capacity in the region, allowing scientists to become leaders in developing new technologies and climate models on the regional level. We have selected a number of cases that can be considered as indicative examples of the type and level of atmospheric chemistry research that has been conducted in the region around two major issues, namely urban air quality and the long-range transport of air pollutants.

**Urban air quality research.** Air quality is a public health issue throughout the world with an estimated seven million premature deaths caused by indoor and outdoor air pollution in 2012 (Lim et al. 2012; WHO 2014b). The LAC region is not an exception and urban air pollution remains a significant public health issue. During the last few decades there has been a large increase in the number of vehicles in most urban and semiurban areas in the region (Romero-Lankao 2007; CEPAL 2010; Gallego et al. 2013) and countries are industrializing (West and Schandl 2013). This has resulted in poor air quality and many LAC governments view this as a major public health problem. Some air pollution events are enhanced as a result of particular geographic and atmospheric conditions. For example, in Santiago, Chile, the combination of thermal inversions and complex terrain results in acute air pollution episodes (Saide et al. 2011b). Complex topography, especially near the Andes, creates ideal conditions for having high levels of air pollution. As a result, even relatively small cities report poor air quality, especially during winter when wood burning is still used for heating (Toro et al. 2006; Díaz-Robles et al. 2008).

Monitoring networks have been established by and for local and national governments in many cities throughout the LAC region to monitor air quality and establish air pollution control strategies. Although these networks were not built for scientific research purposes, they have greatly contributed to a better understanding of the local and regional atmosphere. An example of local efforts addressing measurements of air quality can be found in Bogota, Colombia. Since 1997, 13 automatic air quality stations (12 stationary and 1 mobile) measure common air pollutants. Datasets are available to the public on the city’s Secretary of the Environment website (http://oab.ambientebogota.gov.co/es/indicadores?id=1&v=1) (Gaitán et al. 2007). Even though this monitoring network has suffered operational problems at times, something relatively common in LAC cities, this information has been very valuable for designing air pollution abatement measures, estimating health benefits from these measures, and prioritizing air quality research needs (Ortiz and Rojas 2013). In general, the air pollution monitoring networks in the LAC region could benefit from common data quality assurance and control protocols. This is particularly important regarding speciation of hydrocarbons and the characterization of particulate matter (Vargas et al. 2012).

In other cases large field campaigns, such as the Mexico City Metropolitan Area (MCMA) field campaign in 2003 and the Megacity Initiative: Local and Global Research Observations (MILAGRO) field campaign in 2006, have played an important role in understanding atmospheric chemistry in the region and creating scientific capacity in Mexico (Molina et al. 2010 and references therein). More recently, researchers from Buenos Aires, Argentina; São Paulo, Brazil; Santiago de Chile; Bogota; Medellin, Colombia; and Lima, Peru, developed the South American Emissions, Megacities and Climate (SAEMC) project, sponsored by the Inter-American Institute for Global Change Research (IAI). SAEMC improved emission inventories, developed chemical weather forecasting tools at the continental and city scales and optimized the design of monitoring networks (Martins et al. 2006; Martins and Andrade 2008; Saide et al. 2009; Alonso et al. 2010; D’Angiola et al. 2010; Longo et al. 2010; Freitas et al. 2011; Saide et al. 2011a,b; Gallardo et al. 2012; Longo et al. 2013; Osses et al. 2013).

Remote sensing techniques have been applied for atmospheric chemistry research in the LAC region in order to retrieve ground-level and vertical profiles of air pollutants and other relevant atmospheric gases. For instance, the temporal variability of NO2 has been studied in Mexico, El Salvador, and Argentina by using differential optical absorption spectroscopy (DOAS; Alberti et al. 2012, p. 165; Raponi et al. 2012; Rivera et al. 2013). The DOAS technique has also been used to study industrial and volcanic emissions, for example, the Network for Observation of Volcanic and Atmospheric Change (NOVAC), a European Union funded project (Grutter et al. 2008; Rivera et al. 2009). In addition, greenhouse gases and other pollutants have been measured in the region using Fourier transform infrared spectroscopy (FTIR) methods (Bezanilla et al. 2014; Grutter et al. 2014). There are also significant lidar capabilities in the LAC region for the study of tropospheric aerosols, industrial pollution, and biomass burning (Antuña et al. 2012; Ristori et al. 2012; Lopes et al. 2014). Existing lidar teams in the LAC region are collaborating through the Latin American Lidar Network (www.lalinet.org), which is a contributing network to the WMO GAW Aerosols Lidar Network (GALION). There are also many sun photometers located in the LAC region that are used
to characterize aerosols, for example, to study the maritime mixed aerosols in Camagüey, Cuba, and the intraseasonal variability of smoke during a biomass burning season in South America (Estevan et al. 2011; Rosário et al. 2013).

In spite of expanding economies, research spending, and scientific output over the past two decades, research communities in general and atmospheric chemistry communities in particular are still small in most of the LAC countries (Van Noorden 2014). According to a systematic search using the Scopus database, Brazil, specifically the University of São Paulo, leads by far in research and scientific publications on atmospheric science subjects in the LAC region. Many studies are also related to the health effects of air pollution (Brito et al. 2013). Therefore, scientific capacity building remains a foremost requirement to addressing the issues associated with growing cities such as air quality and climate change. Material and human resources for atmospheric research in the LAC region, possibly with the exception of large cities/states in Brazil, are insufficient. This makes it difficult to conduct high-level research, contribute to international programs, and influence sustained impacts in local development. That is why air quality and climate researchers critically need regional collaborating networks and significant investments in capacity building at various levels. Within this framework, it is important to acknowledge the contribution of large international campaigns and projects like MCMA, MILAGRO, and SAEMC not only in increasing the scientific understanding of atmospheric processes in LAC cities but also in building scientific capacity within the region through training, participation, and coauthoring scientific publications with local and international scientists. Local research initiatives have produced a number of interesting results in relation to urban air quality and small groups have been increasing their capabilities both in infrastructure and scientific/technical expertise. As a result, they are addressing broader and deeper research questions emerging from the rapid changes in the region.

**Long-range transport of pollutants.** Urban and rural air quality in LAC countries is often impacted by the long-range transport of air pollutants that are produced within and outside the region and transported under the right meteorological conditions. Examples of long-range transport are dust from Africa, specifically the Sahara/Sahel region, and smoke produced by biomass burning from central Africa. Examples of regional transport are smoke from agricultural fires and anthropogenic pollutants within the continent (i.e., smoke from the Amazon reaching the Andes).

Dust transported from North Africa across the Atlantic to the Caribbean basin and the central United States occurs mostly from June to August (Husar et al. 1997; Perry et al. 1997; Prospero 1999; Nowottnick et al. 2011; Prospero and Mayol-Bracero 2013). A southward displacement of the dust cloud in the winter months transports dust into South America, as seen in satellite products and characterized by measurements over the Amazon (Swap et al. 1992; Husar et al. 1997; Prospero 1999; Martin et al. 2010; Huneeus et al. 2011). The transport of African dust causes severe impacts on the air quality of receptor countries (e.g., reduction in visibility, poor air quality) (Prospero et al. 2008; Bozlaker et al. 2013; Prospero and Mayol-Bracero 2013; Prospero et al. 2014; Ortiz-Martínez et al. 2015). African dust has also been shown to have an impact on hurricanes, precipitation, clouds, climate, and ecosystem health (Swap et al. 1996; Dunion and Velden 2004; Koren et al. 2006; Bristow et al. 2010; Okin et al. 2004; Prospero and Mayol-Bracero 2013; Spiegel et al. 2014; Raga et al. 2016; Valle-Diaz et al. 2015). This happens mostly during the Northern Hemisphere winter-time when African dust reaches northeastern South America. This African dust has been shown to have a positive impact on the Amazon forest as a result of the input of nutrients (Artaxo et al. 1990; Swap et al. 1996; Husar et al. 2004; Koren et al. 2006; Ansmann et al. 2009; Ben-Ami et al. 2010; Bristow et al. 2010; Martin et al. 2010). Many important questions still remain regarding the importance of the long-range transport of dust and its impacts on the Earth’s biogeochemistry cycle (Okin et al. 2004).

Biomass burning smoke within the Amazon basin occurs in the austral winter/spring primarily because of land clearing. Fires generated in Brazil, Bolivia, Paraguay, and Argentina emit smoke that is then transported locally and regionally (Fig. 3) (Freitas et al. 2005; Evangelista et al. 2007; Longo et al. 2009; Pereira et al. 2011). Amazonian biomass burning plumes have been observed in LAC countries such as Suriname and Venezuela (Andreae et al. 2001; Hamburger et al. 2013). In addition, smoke produced by biomass burning in the Bolivian lowlands and, possibly, Brazil, Argentina, and Paraguay, has been measured high in the central Andes, suggesting that the convective transport of biomass burning plumes is of importance to the region (Andrade et al. 2011; M. Andrade et al. 2016, in preparation). Heavy smoke from forest fires in the Amazon basin has been observed to shift precipitation formation in convective clouds to greater heights and thereby...
impact the water cycle, the pollution burden of the atmosphere, and the dynamics of atmospheric circulation (Andreae et al. 2004). Studies performed by Lau et al. (2010) over the Himalayas suggest that black carbon (BC) from biomass burning in South America, transported to the Andean glaciers, cannot only decrease the albedo of ice/snow, but can warm the local atmosphere, further contributing to the melting of glaciers in the Andean region. This suggests that both the ice/snow albedo effect and the warming of the atmosphere resulting from BC likely have contributed to the rapid observed rate of glacial melting, which impacts freshwater security in the Andean region. As a result, an area of current research is the impact of biomass burning smoke from the Amazon basin on precipitation patterns and the enhanced melting of glaciers (Molina et al. 2015). It is important to note that besides biomass burning there are multiple sources of BC in the LAC region: diesel vehicles, industrial sources, residential burning of wood and waste for heating and cooking, and informal burning kilns for brick production, etc. Several studies have addressed the long- and short-range transport of urban and wood burning aerosol over the Andes (Longo et al. 2009; Pereira et al. 2011; Cereceda-Balic et al. 2012; Rosário et al. 2013; Mena-Carrasco et al. 2014; Schmitt et al. 2015).

MAIN SCIENTIFIC QUESTIONS AND KEY STEPS FORWARD. The foci of scientific questions may differ significantly depending on the specific needs within the LAC region, but it is nevertheless possible to generalize some main questions that have, and can, be commonly addressed. First, it is important to examine the link between air pollution and climate in more depth, which is crucial for understanding the feedback mechanisms involving short- and long-lived species. For example, the forcing and impacts of short-lived climate pollutants (SLCPs) on air quality and climate, the changes in boundary layer processes including the heat island effect and stratification over complex terrain, and the effect of increasing temperatures on photochemistry are not well understood in the LAC region. The aforementioned links between air pollution and climate govern how air pollutant emissions result in ambient concentrations, which have direct impacts on human health and ecosystems. The development of local, national, and regional emission inventories is a critical scientific need in the LAC region in order to address air quality and climate considerations. Long-range transport is another main theme among the remaining scientific questions regarding the fate of African dust and biomass burning plumes and their impacts on cloud formation, urban air pollution, and freshwater security. In addition, the transport of particulate matter and gases from the near surface to the free troposphere over complex terrain is another area of scientific interest in the Andean region. The evolution of urban and industrial plumes, on the other hand, may affect atmospheric composition, cloud processes, and pristine environments (glaciers, biomes, protected areas, oceans, etc.). There is still more to learn about how the intercontinental transport of dust impacts the biogeochemical cycles of the oceans and in the ecosystems in the LAC region and how it impacts air quality, clouds, and storm formation. The extent of how natural (volcanic, biogenic, and oceanic) emissions contribute to the overall loading of aerosols and gases and how they are involved in various atmospheric processes is not fully understood. Finally, the impacts of future changes on the composition of the atmosphere associated with climate change and rapid land-use change in the LAC region have not been fully studied. Many of these issues are not exclusive to the LAC region but are global in nature and will require international collaboration to be fully understood.

To address the issues mentioned above, there is an urgent need to increase the number of qualified
scientists and specialized technicians in the LAC region. Some countries have shown significant advances in establishing research groups and high-level educational programs, but the growth in the number of experts has been slow and geographically uneven. Most LAC scientists are educated in developed countries but often cannot find adequate research positions in their home countries. There is a need to lure these scientists back to the region by developing an adequate infrastructure from the level of local institutions to national governments. Moreover, there is an appalling need to improve the observational, analytical, and modeling capacities, which in turn requires sustained, prioritized, and oriented funding. Convincing governmental agencies about the socioeconomic benefits of investing in research in environmental problems is a challenge to the community. Finally, since alliances with the United States and Europe have been favored over regional collaborations, even in cases when regional expertise is available, a key component to overcome is the current limitations to fostering stronger collaborations among LAC research groups.

The iCACGP/IGAC AWG is stepping forward to address these and other questions that may arise as the LAC region faces new and more complex environmental problems. Addressing these issues requires a strong cohesive community of atmospheric scientists within the region and the coordination of activities among the research community to foster collaborative projects by means of specialized courses, thematic workshops, and exchange programs. We therefore invite these scientists to join the iCACGP/IGAC AWG to help create a more collaborative atmospheric chemistry community in the LAC region (sign up for the iCACGP/IGAC AWG e-mail list at http://eepurl.com/-dSCr).

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REFERENCES


Ortiz, E. Y., and N. Y. Rojas, 2013: Estimación de los beneficios económicos en salud asociados a la...


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LETTER FROM HEADQUARTERS

VOLUNTEERING IS EASIER THAN IT LOOKS

In the June installment of this column I discussed the value of membership and how that is amplified if you volunteer for the Society because it is through that volunteer service that AMS can really enhance one’s career and enjoyment in the profession. The structure of AMS boards and committees (of which there are more than 100) can seem daunting, however, and some people who want to volunteer never get past this feeling and simply wait for an invitation to serve on a committee or board. An invitation is only likely, though, if they already know someone who is currently serving.

If you have felt intimidated by the complexity of the AMS structure, I encourage you to take a little time to break down that mental barrier. View the rich organizational framework of boards and committees as a simple sign that there are multiple opportunities to engage in areas that truly interest you. Once you get even a cursory sense of the commission structure that frames the Society’s volunteer opportunities, the system becomes pretty easy to navigate. And getting involved becomes easier than you think, because each of these smaller groups within the structure is actually a much less intimidating point of contact for inquiring about volunteering.

We will explore this structure briefly here so you can get a sense of it and how you might contribute. Nearly all boards and committees reside within one of the six overarching commissions. To illustrate this, let’s look at the Commission on Professional Affairs, which oversees activities for professional growth, including AMS certification programs. This commission’s page on the AMS website (www.ametsoc.org/cprof/) gives a brief overview and lists the boards under the commission, with links to their individual pages.

If, for example, you think you might be interested in serving on the Board on Early Career Professionals, you have several ways to proceed. On the board’s page you can get the contact information for the current board chair, and you can e-mail the chair directly to learn more about possible service on the board. If you prefer, you can also e-mail the commissioner (a volunteer who helps coordinate the activities within the commission) using the contact information provided on the commission-level page. These are people who typically are looking for ways to involve more people like you in their activities. And if they don’t have a slot on the specific board or committee you initially inquire about, they often know of similar opportunities in related areas within the AMS structure.

If you are not comfortable reaching out directly to one of these individuals—though there is no reason to be shy—fill out the “Volunteer Form” provided on the “Find Ways to Volunteer” page (follow the “Get Involved” link at the top right of virtually every page of the AMS website). Include in the form a little bit about your interests and/or the boards or committees you think might be the best fit for you. We will do our best to get that information to the appropriate commissioner(s) who ultimately make the appointments. (You should note that a few boards and committees have requirements that must be met to serve, such as the CCM Board, which is only open to those who have already earned that certification, but most boards and committees are open to all.)

Be sure to explore the other commissions that provide great opportunities for service: the Education and Human Resources Commission, which addresses educational and workplace environment issues; the Publications Commission, which oversees the peer-review process for the Society’s journals and other publications; the Scientific and Technical Activities Commission (STAC, which is pronounced “stack”), which monitors the science in the disciplines AMS covers as well as organizing most of the scientific conferences held by AMS; and the Weather, Water,
and Climate Enterprise Commission, which broadly seeks to improve cooperation among the government, private, and academic sectors and the effective utilization of our science. All of these commissions actively encourage early- and midcareer individuals to serve, and all welcome student members, as well. The sixth commission is the Planning Commission, which is the strategic planning arm of the Council. There are also great opportunities to serve as a volunteer for committees that are not under the six commissions and that report directly to the Executive Committee or the Council, such as the Local Chapter Affairs Committee and the Committee on Environmental Stewardship.

The message here is that there are many opportunities to enhance your career and get the most out of your membership through service to the community within the Society no matter what aspect of our profession you are most interested in. The many current volunteers, which number more than a thousand, will truly welcome hearing of your interest.

If you have any questions about how to volunteer for service (or on any other aspect of AMS), please do not hesitate to contact me (e-mail: kseitter@ametsoc.org, phone: 617-226-3901). I work for you, after all, and interacting with members of the community is one of the most enjoyable parts of my job.

Keith L. Seitter, CCM
Executive Director

MEET THE AMS

WENDY ABSHIRE
AMS Education Program Director

Wendy (Schreiber) Abshire distinctly remembers the moment she set her sights on becoming a meteorologist. She was nine years old in the fourth grade in Phoenix, Arizona, and her class was studying weather.

“I asked my teacher, Miss Fields, ‘Can you do weather as a job?’ and she said, ‘Yes, it’s called being a meteorologist,’ and that was that!” Wendy remembers.

She attributes her passion for the field to having grown up in “the West,” where she routinely experienced mountain snowstorms, downslope windstorms, haboobs, and intense lightning associated with southwest monsoon storms, and where she watched dry creek beds fill with flash floods while hiking in the desert.

Wendy joined AMS staff this fall as the new Education Program director following Jim Brey’s retirement as director.

“I’m excited at the prospect of supporting well-established AMS programs such as DataStreme, the Maury Project, and Project Atmosphere,” Wendy says. “I want AMS members to know that the AMS Education staff creates and delivers top-notch geoscience textbooks on weather, ocean, and climate studies that are far better than the one I was studying back in fourth grade!”

Wendy studied meteorology at Metropolitan State College in Denver, receiving her B.S. degree and then staying out west to earn her M.S. in atmospheric science at the University of Wyoming. She greatly benefitted from the solid education, small class size, and personal attention she received as a part of both departments.

“While doing my graduate work, I vividly recall watching a tornado from the airplane while conducting research from the Wyoming King Air,” Wendy notes. “And I try actively not to remember how I felt all summer in the back of the hot plane changing data tapes while flying in the convective boundary layer gathering valuable data. Fieldwork is not always pretty.”

Ten years after her conversation with her teacher, and while an undergraduate, Wendy began work as a student assistant at the National Center for Atmospheric Research (NCAR) in Boulder. She was immediately put to work analyzing data from the groundbreaking Joint Airport Weather Studies Experiment, which changed the way the world understood microburst aviation hazards. She was also fortunate enough to be paid to chase storms and coauthor an important Monthly Weather Review paper with Jim Wilson titled, “Initiation of Convec-
itive Storms and Radar-Observed Boundary-Layer Convergence Lines.” One of her most memorable experiences from her NCAR days was the night during the Microburst and Severe Thunderstorm experiment that she spent with a C-band Doppler radar playing back the day’s data and analyzing it with Tetsuya “Ted” Fujita.

“He simply couldn’t wait to get another look and begin unraveling the mystery of moist microbursts,” Wendy recalls. “He was the most passionate atmospheric scientist I’ve ever met.”

Except for graduate school, Wendy remained at UCAR for 33 years, 26 of which were in a variety of roles with the Cooperative Program for Operational Meteorology, Education and Training (COMET). Following graduate school, she was fortunate enough to return to UCAR working for the fledgling COMET Program, which was just beginning to develop new methods for delivering continuing education to professionals in support of the nation’s weather services, and in particular, the National Weather Service Modernization during the 1990s.

“It was exciting to work with renowned experts, creative instructional designers, programmers, and graphic artists to make interactive self-paced training before ‘multimedia’ was something we all knew and appreciated,” says Wendy. “The first lessons on laserdisc even included a ‘mouse tutorial’ to teach users how to interact with the screen using their PC mouse. That’s how early we got in the business!”

Now, after evolving from laser disc, to CD-ROM, and on to the Web, COMET is primarily known around the world as the creators and keepers of the MetEd Website (www.meted.ucar.edu).

“The reach that COMET has, providing online geoscience training to nearly half a million people in the last nine years, far exceeds any of our wildest dreams,” Wendy says. “I’m so proud to have been a part of what my former coworkers and colleagues have accomplished!”

Throughout her career, Wendy has been involved with the AMS and National Weather Association (NWA). She has been a member of the AMS and the Denver-Boulder local AMS chapter since 1983, and has been a local chapter officer several times. Her local service led her to involvement with and serving as chair for several national AMS committees, including the Board on Outreach and Precollege Education, the Local Chapter Affairs Committee, and the Membership Committee (including helping to form the AMS Beacons program); most recently, she has contributed in the roles of AMS Councilor and planning commissioner. She was also honored to serve the NWA not only as a long-time member but also as Councilor and vice president. Wendy has always been dedicated to mentoring students, including serving as a nine-time mentor to some brilliant young minds via UCAR’s Significant Opportunities in Atmospheric Research and Science (SOARS) Program. Following her participation in the first AMS Policy Colloquium and UCAR’s Leadership Academy, Wendy was approached to serve in another capacity and become one of the first ombudspersons at UCAR.

“When I was asked, I had no idea what was being asked of me,” she explains. “An organizational ombudsman is a designated neutral or impartial dispute-resolution practitioner whose major function is to provide independent, impartial, confidential, and informal assistance. By working as an ombuds, I have learned to be a better listener, to have a better understanding of interpersonal conflict, and to really feel the joy of investing in others to help create the best possible workplace.”

In her role as director of the Education Program, Wendy also plans to work with the AMS Board on Continuing Professional Development and investigate a variety of collaborative opportunities to bring new continuing education offerings to AMS members and partners.

“All these activities work toward our program’s common goal of increasing public scientific literacy,” she says, “and I can’t think of a better reason to head into the office each day.”

When she’s not working or serving the field in one capacity or another, Wendy takes great pleasure from being near her parents, being the proud mother of two “twenty-something” sons, and being happily married to her best friend.

“I absolutely couldn’t have managed my career and life without all the loving support of my family,” she says.

In her free time, she loves to hang out with friends on her patio, hike, camp, make cards, send and receive snail mail, and bake cookies.

—Rachel S. Thomas-Medwid
10 QUESTIONS WITH...

A new series of profiles celebrating AMS Certified Broadcast Meteorologists and Sealholders

Irene Sans
Digital Meteorologist/Web Weather Producer, WFTV, Orlando, Florida

What inspired you to go into broadcasting?
I got into meteorology because I fell in love with the science while in middle school. I was not completely sure I was going to go into broadcasting, but then I saw the need for accredited Spanish-speaking broadcast meteorologists, so I decided to pursue it. Back then, the only markets that had accredited Spanish-speaking meteorologists were Miami and Puerto Rico. Today, almost 10 years later, less than half a dozen have them. There is still a lot of work to be done.

How has the field changed since you started?
There have been several advancements in the science itself. Dual polarization of radar, for example, has been a great tool for broadcast meteorologists, especially in weather-driven markets. Computer systems we use have also made huge improvements. When I started, radar and satellite imagery had to be rendered, and building a graphic was hard work. Now, we’re able to have the latest available radar image and not have an extra delay.

What is the best thing about what you do?
I feel most proud and moved when kids come up to me and tell me that I sparked their interest in meteorology or science. When you get an e-mail, message, or even call to say “Thank you for keeping me informed, your forecast and recommendations helped me make the right decisions for me and my family,” this takes me to a full circle and reminds me about the great professionals that influenced me and guided me.

What does being a “station scientist” mean to you?
A majority of the news could be science-related many times. In 2014, a major earthquake occurred in Iquique, Chile; using our weather computer systems I was able to provide a quick location map for the news, and also talked about the plate movement in this region of the world.
wanted to get out of university after my master’s, but Professor Wanner offered me a position within an EU project on climate change during the Maunder Minimum, a very cold period in Europe, and I accepted. I found this very interesting to work scientifically, internationally in a European project, and my part was to work on the Maunder Minimum climate and to reconstruct climate during the period around 1700. So, I made my Ph.D. there and [then] I got an offer in Bern to do a postdoc on paleofloods with Professor Wanner and Professor Pfister. This was also in collaboration with German and Czech partners [and] I found this very fruitful to work interdisciplinary but also internationally. Then, I did my habilitation there. I collected all the papers we published in the team over the past five years, and then I got an offer from the University of Heidelberg in geography and at the same time the University of Giessen. And, I found the environment [in Giessen] much better, the offer was much better, and the people I liked very much there—so I accepted the offer. And I was a couple of months at the University of Arizona in Tucson and also in Beijing. I got an offer also from Cyprus, but I then decided to stay in Giessen, which is a very nice environment to develop climate sciences.

Kuglitsch: How did these positions and working with scientists from different institutes and countries influence the direction of your research? In other words, how important is interinstitutional and international collaboration for developing (and answering) your research questions?

Luterbacher: I think, as in many other parts of climate science, especially in paleoclimate science, it’s very important to have a very good network (col-
fields but working together and bringing the experts and that makes it very interesting to go in different and space scales, and we want to understand the changes, in the past–present–future on different time focus in terms of hydrological changes, temperature have a widespread difference of projects with different behind it. So, what we try in our research group is to be applied or time series analysis, or just the idea somehow they're connected with the methodology completely different in what they want to study, but specific problems of climatology, and they might be aspects, we have different assistants that work on a couple of projects, and they deal with different pect within geography and climatology. So, we have different climate but to be really broad. This is also an as the University of Bern, not to study specific aspects Luterbacher: well, that's the way I was educated at the field of geosciences for 2015. In that year, you had three articles in the Journal of Climate: a study about simulated daily precipitation, a study about the early nineteenth-century summer cooling in central Europe, and a study about surface air temperature records over Antarctica. Although each of these studies falls within the field of climatology, they cover a broad range of topics, time scales, and spatial scales. This is consistent with your research and publication history. How do you find a balance between considering the interconnections between climate change and forcings on various spatial and temporal scales, and not becoming overwhelmed? How do you maintain a holistic view of the climate system but filter out the noise? Luterbacher: Well, that's the way I was educated at the University of Bern, not to study specific aspects of climate but to be really broad. This is also an aspect within geography and climatology. So, we have a couple of projects, and they deal with different aspects, we have different assistants that work on specific problems of climatology, and they might be completely different in what they want to study, but somehow they're connected with the methodology to be applied or time series analysis, or just the idea behind it. So, what we try in our research group is to have a widespread difference of projects with different focus in terms of hydrological changes, temperature changes, in the past–present–future on different time and space scales, and we want to understand the climate behind, the dynamics, the processes, from different aspects. We have the experts in our team and that makes it very interesting to go in different fields but working together and bringing the experts to the same time table, and everyone can contribute and learn despite the fact that the topics might be completely different. Kuglitsch: Speaking of being overwhelmed, you give lectures, you have administrative roles as the head of the Geography Department, you actively conduct and publish research, you are the editor for several journals, you are the reviewer for even more journals, you regularly attend international conferences, you were an author of the fourth and fifth IPCC reports, and—most importantly—you have a beautiful family. How do you find time to fulfill your professional responsibilities and maintain a healthy work/life balance? Can you offer any tips or strategies? Luterbacher: Well, this is actually not very easy to answer. But, so far I’ve managed, and this only works if you have a really good functioning team at the university with reliable, very motivated people that can work interdisciplinary and independent, so I don’t have to be there all the time, they know what to do, they can interact with each other, they can work, they know the work they have to do and want to do, [and] they talk to each other. So you need to have a very good team that understands each other in terms of science, doing the science, to publish the science, but also interact on a social basis. And, of course, it needs a family that understands that you have to work, maybe sometimes more, but of course it also means that you find time for the family for other aspects, really to get other ideas than science and to be full of energy for other aspects. Kuglitsch: Finally, looking back at your career to date, what advice can you offer students or young scientists? Luterbacher: I think it’s very important for a person that looks for a job—a Ph.D. or postdoc—that you really first of all consider what you want to do, that you make a plan—o.k., I see myself in three or five years, that’s what I want to reach, that’s what I want to become, [and] that’s what I want to learn—and to find a position in an environment that really suits you. You have to see what the people are doing. Does the supervisor have a very good publication track? Is he a good supervisor? So you might ask people who were already in the group their experience with this group, with this promotor, with this supervisor. And, the supervisor should really have time to work with these people—to promote them—because the supervisor usually has a permanent position but it is his or her duty actually to promote the people so that they can develop themselves, they can publish, they have freedom to do the research, they can meet, they can go to EGU or AGU to exchange ideas, to learn, to present,
The AMS Speaks Out—on Weather, Water, and Climate Priorities

Originally posted on July 20, 2016

"Understanding how the Earth system works and transforming this knowledge into action will allow our nation and the global community to effectively respond and adapt to changing weather, water, and climate conditions. National investment and leadership combined with enhanced partnerships across the public, private, academic, and nongovernmental organization sectors are necessary to make this vision a reality."—from the 2016 AMS Policy Statement on Weather, Water, and Climate Priorities

"Seek first to understand, and then to be understood."—Stephen Covey’s Habit 5.

"Speak properly, and in as few words as you can, but always plainly; for the end of speech is not ostentation, but to be understood."—William Penn

For nearly 100 years, members of the AMS have banded together seeking to understand two things.

First, how do the Earth’s oceans and atmosphere work? What governs their structure, and their movement, the cycles of seasons and years? Why do they accomplish so much of their business through acute, highly localized and dangerous extremes of flood and drought, high winds, and more? This first task has proved daunting, has preoccupied AMS meteorologists, oceanographers, and scientists from related disciplines for most of the 100 years, and continues to challenge today.

Second, how can that understanding be applied—moment by moment, and place by place as well as globally—for societal benefit? As this second challenge has moved to the fore, it has proved to be as complex and stubbornly resistant to progress as the first. Ever-changing weather threats and the highly localized weather vulnerabilities of public safety, agriculture, energy, and transportation combine to make the value of weather information both uncertain and perishable. Communicating meteorological understanding in ways that its implications for public safety, agriculture, energy, transportation, and more can be understood and acted upon is proving equally demanding.

Most of the time, the energies of weather and climate forecasters and water resource managers are devoted to meeting these unrelenting, moment-by-moment societal needs. But every so often, it’s possible, and indeed necessary, for Earth scientists and the practitioners providing related science-based services to take stock of their work in the broader context of human affairs—to understand, and to be understood in a different way.

The summary to the AMS statement quoted above makes clear a circular logic:

1. On the one hand, the future of society depends on the quality, relevance, and timeliness of environmental intelligence. To quote the AMS statement: Access to reliable, accurate, timely, and understandable weather, water, and climate (WWC) information is vital for the safety and well-being of society. Decision-makers at all levels need this information to formulate and implement effective strategic, tactical, and policy decisions across all interconnected sectors of society, including health, energy, food, water, infrastructure, transportation, and national security. Extreme weather events like hurricanes, tornadoes, blizzards, floods, wildfires, severe coastal storms, and heat waves, and the impacts of longer-term climate changes such as droughts, changing
snowpack, and sea level rise threaten the social and economic security of our nation and society as a whole. While these challenges pose serious risks, they also offer a remarkable national opportunity for enhanced knowledge, advanced tools, leadership, and actionable information.

WWC observations, science, and services are critical national infrastructure essential for meeting human needs. They have led to technological innovations, fueled economic growth, stimulated social prosperity, and mitigated potential WWC-related disasters...

...The value of WWC tools and information to economic growth is increasing as is the cost of WWC-related disasters. Individuals and business and government leaders are shaping decisions and actions based on detailed knowledge of meteorological, hydrological, oceanographic, geophysical, and ecological conditions, and on an understanding of how society responds. As society responds to the increasing frequency and severity of extreme WWC events, it needs and expects ever more reliable and actionable information to deal with pressing local, regional, national, and global economic and societal challenges that can range in time scales from minutes to centuries.

2. On the other hand, good environmental intelligence is possible only with sustained, comprehensive societal support. To quote the AMS statement:

AMS public, private, and academic-sector members acknowledge the ongoing vital commitment and support of the American public and its leaders to the advancement of WWC observations, science, and services. This support improves forecasts, makes new information products possible, trains the next generation of scientists and decision-makers, and enables more effective communication. As a result, people have been better prepared for disruptive WWC events, and many lives have been saved.

The AMS statement notes that this societal support takes several forms, and accordingly makes seven recommendations:

1. Develop the Next Generation of WWC Experts. To ensure we have a diverse workforce equipped to communicate uncertainties and inform WWC decisions, investments must continue to: (i) educate and train students for careers in science, technology, engineering, and mathematics; and (ii) develop the next generation of WWC researchers that can advance the science and its applications to meet society's evolving information needs.

2. Invest in Research Critical to Innovation and Advanced Services. To ensure continued leadership in understanding our complex and changing planet and application of this understanding for the benefit of society, increased investments are needed to support new discoveries, innovation, applications, and model development in the geosciences, engineering, and relevant social sciences.

3. Invest in Critical Observations and Computing Infrastructure. To ensure advances in scientific knowledge and more accurate and timely delivery of WWC products and support services at scales useful to decision-makers, and to preserve national security, targeted investments are required for: (i) atmosphere–ocean–land–ice observational infrastructure, (ii) techniques to translate the resulting large datasets into forms suitable for information services and prediction models, and (iii) leading-edge high-performance computers and software.

4. Create Services that Harness Scientific Advances for Societal Benefit. To ensure society's most pressing needs are met and its capabilities are optimally utilized, mechanisms for engaging users and moving research into practical applications in a timely and effective fashion must be encouraged, developed, and implemented.

5. Prepare Informed WWC Information Users. To ensure we have informed users who can take full advantage of advanced WWC information and tools, education and communication programs must continue to focus on enhancing WWC skills and understanding by both decision-makers and society at large.

6. Build Strong Partnerships Among WWC Public, Private, and Academic Sectors. These sectors have always worked together to meet America's WWC challenges. As the job grows more consequential, urgent, and complex, a coordinated Federal effort is needed to support, strengthen, and encourage strategic inter-sector partnerships, including efforts to increase the global suite of Earth observations, advance long-term stewardship of environmental data, and improve national and international community-level resilience to climate change and variability.

7. Implement Effective Leadership and Management. To ensure that WWC investments are made in the
After nearly 41 years, Thomas Karl, director of NOAA’s National Centers for Environmental Information (NCEI), is retiring from federal service. He chaired the 13-federal-agency, multibillion-dollar U.S. Global Change Research Program (USGCRP). He is a Fellow of AMS and has served as its president and as a member of the Executive Council.

Karl obtained his bachelor’s degree from Northern Illinois University and his master’s degree from the University of Wisconsin—both in meteorology. After finishing his master’s degree, he applied for several positions across the country, including one at what was then the Environmental Research Lab in Raleigh, North Carolina, and he was offered the position. He began researching the interactions of air pollution with Earth’s climate.

After a stint as a weather forecaster with the National Weather Service Office in Anchorage, Alaska. Karl joined the National Climate Center in Asheville, North Carolina, in 1980. Since then, the National Climate Center transformed into the National Climatic Data Center. Throughout that time, Karl also worked his way up from a researcher to a lab chief to senior scientist to director of the center. And, when the National Climatic Data Center merged with its sister data centers in 2015, Karl took on the responsibility of serving as NCEI’s first director and shepherding the former organizations through the transition period.

Karl has published more than 190 peer-reviewed scientific reports and articles and has authored several books as an editor and contributor. He has received many awards and recognition for his services and scientific research in climate-related work, including two Distinguished Presidential Rank Awards, five gold medals and two bronze medals from the Department of Commerce; the AMS’s Suomi Award; the NOAA Administrator’s Award; designation as a National Associate of the National Academy of Sciences; and several others. He has served as editor of the Journal of Climate and has been a convening...
AccuWeather announced that the University of Oklahoma (OU) Office of Technology Development has signed a patent licensing agreement for the use of AccuWeather’s proprietary patents to benefit university advancements in technology innovation, including OU’s Meteorological Phenomena Identification Near the Ground mobile app (mPING).

Under the new agreement, the university will integrate a range of AccuWeather’s location-based patents worldwide, which cover the ability to geographically pinpoint all forms of content across all wireless platforms to individual users and to their dynamically changing locations.

AccuWeather’s patents will be used in the mPING mobile app, which was developed through a collaboration between NOAA’s National Severe Storms Laboratory and OU’s Cooperative Institute for Mesoscale Meteorological Studies (CIMMS), allowing users to anonymously submit weather observations and view reports all around the world on Android and iOS devices. AccuWeather meteorologists and technology experts will begin collaborating with CIMMS to refine and enhance the mPING app through the integration of AccuWeather’s patents.

Sumant Nigam has been named a 2016–17 Jefferson Science Fellow by the U.S. Department of State and the U.S. Agency for International Development (USAID). The innovative fellows program engages the nation’s academic scientists, engineers, and physicians in U.S. foreign policy.

Nigam is a professor in the Department of Atmospheric and Oceanic Science and the Earth System Science Interdisciplinary Center at the University of Maryland. Nigam studies atmospheric general circulation and teleconnections, climate dynamics, tropical ocean–atmosphere interaction, aerosols and Asian monsoon, and Great Plains hydroclimate variability and droughts. One of Nigam’s current research projects involves unraveling the natural variability and secular change components of the climate record to advance understanding of the recent warming of the northern continents.

He chairs the AMS Climate Variability and Change Committee and the Advisory Panel for the National Center for Atmospheric Research’s Climate and Global Dynamics Laboratory, and serves on the International Commission on Dynamical Meteorology.

Nigam is a Fellow of AMS and the Royal Meteorological Society. He earned his master’s degree in physics from the Indian Institute of Technology in 1978 and his Ph.D. in geophysical fluid dynamics from Princeton University in 1984; he held a postdoctoral position at the Massachusetts Institute of Technology from 1984 to 1987.

Fellows spend one year at the State Department or USAID for an on-site assignment in Washington, D.C., that could involve extended stays at U.S. foreign embassies and missions. They will remain available to the U.S. Department of State/USAID for short-term projects over the subsequent five years.

Chris Gloninger joined NECN and NBC Boston this past June.

Previously, Gloninger worked at WISN in Milwaukee, where he won an Emmy for his winter storm coverage and several Wisconsin Broadcasters Association awards. He began his career at WHEC in Rochester, New York, where he also taught “Intro to Meteorology” at Monroe Community College. He then joined WTEN in Albany, New York. At WNEM in Saginaw, Michigan, Gloninger received an Emmy nomination for his coverage of the 2010 Michigan floods. He was nominated for another Emmy at WRGB in Albany, New York, for the weather special, “Irene—One Year Later,” which covered the progress made after the historic flooding in the Schoharie Valley.

He received his B.S. in meteorology from Plymouth State University. He received his CBM from AMS and is interested in improving communication between first responders, the NWS, and television meteorologists in order to better protect the public.
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American Meteorological Society
The Executive Committee has approved the election of the following candidates to the grade of **Full Member:**

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</tr>
<tr>
<td>Ricardo Ramirez-Vargas</td>
</tr>
<tr>
<td>Dominik Renggli</td>
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<tr>
<td>David B. Reusch</td>
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<tr>
<td>David Reyes</td>
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<tr>
<td>Regina Rodrigues Rodrigues</td>
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<tr>
<td>Scott C. Runyon</td>
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<tr>
<td>Austin Ruzic</td>
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<tr>
<td>Geun-Hyeok Ryu</td>
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<tr>
<td>Jarkko Sairanen</td>
</tr>
<tr>
<td>Haydee Salmun</td>
</tr>
<tr>
<td>Matt Sampson</td>
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<tr>
<td>Benjamin David Santer</td>
</tr>
<tr>
<td>Sebastian Schemm</td>
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<tr>
<td>Callum James Shakespeare</td>
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<tr>
<td>R. Kipp Shearman</td>
</tr>
<tr>
<td>Andrew Shipotofsky</td>
</tr>
<tr>
<td>Valerie Lynn (Smock)</td>
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<tr>
<td>Stajewski</td>
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<tr>
<td>Peter Steinle</td>
</tr>
<tr>
<td>Mathew Stiller-reeve</td>
</tr>
<tr>
<td>Scott Stripling</td>
</tr>
<tr>
<td>Suaydhi Suaydhi</td>
</tr>
<tr>
<td>Mauro Sulis</td>
</tr>
<tr>
<td>Kosana Suvocarev</td>
</tr>
<tr>
<td>R. G. J. Tailleux</td>
</tr>
<tr>
<td>Zhining Tao</td>
</tr>
<tr>
<td>Lin Tian</td>
</tr>
<tr>
<td>Susan Tolwinski-Ward</td>
</tr>
<tr>
<td>Stephanie Schollaert Uz</td>
</tr>
<tr>
<td>Maarten van Reeuwijk</td>
</tr>
<tr>
<td>Adam C. Varble</td>
</tr>
<tr>
<td>Gizo Vashakidze</td>
</tr>
<tr>
<td>Subhas Karan</td>
</tr>
<tr>
<td>Venayagamoorthy</td>
</tr>
<tr>
<td>R. Venkatesan</td>
</tr>
<tr>
<td>Ricardo Villalba</td>
</tr>
<tr>
<td>Akiyoshi Wada</td>
</tr>
<tr>
<td>Donghai Wang</td>
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<tr>
<td>Robert A. Warren</td>
</tr>
<tr>
<td>Richard Andrew Wehr</td>
</tr>
<tr>
<td>Glenn H. White</td>
</tr>
<tr>
<td>Gabriel Williams</td>
</tr>
<tr>
<td>Arne Winguth</td>
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<tr>
<td>Glenn M. Wolfe</td>
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<tr>
<td>Forrest J. Wrenn</td>
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<tr>
<td>Chuliang Xiao</td>
</tr>
<tr>
<td>Sho Yokota</td>
</tr>
<tr>
<td>Lauren M. Zamora</td>
</tr>
<tr>
<td>Bin Zhang</td>
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<tr>
<td>Haikun Zhao</td>
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</tbody>
</table>

The Council has approved the election of the following candidate to the grade of **Full Member with Student Privileges:**

<table>
<thead>
<tr>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabriele Arduini</td>
</tr>
<tr>
<td>Tyler Louis Casazza</td>
</tr>
<tr>
<td>Manda B. Chasteen</td>
</tr>
<tr>
<td>Kathy Cruz</td>
</tr>
<tr>
<td>Kelley DePolt</td>
</tr>
<tr>
<td>David Dickson</td>
</tr>
<tr>
<td>Bo Dong</td>
</tr>
<tr>
<td>Scott Dubble</td>
</tr>
<tr>
<td>Curtis Edwards</td>
</tr>
<tr>
<td>Phillip S. Harder</td>
</tr>
<tr>
<td>Joseph Ryan Hill</td>
</tr>
<tr>
<td>Michael Hoffman</td>
</tr>
<tr>
<td>Je-Woo Hong</td>
</tr>
<tr>
<td>Tristan Kading</td>
</tr>
<tr>
<td>Elizabeth Klovenski</td>
</tr>
<tr>
<td>Alex Kogan</td>
</tr>
<tr>
<td>Tsubasa Kohyama</td>
</tr>
<tr>
<td>Derek V. Mallia</td>
</tr>
<tr>
<td>Arash Nemati Hayati</td>
</tr>
<tr>
<td>Bryan David Ostrander</td>
</tr>
<tr>
<td>Szandra A. Peter</td>
</tr>
<tr>
<td>Rick Russotto</td>
</tr>
<tr>
<td>Shayak Sengupta</td>
</tr>
<tr>
<td>Ken Tay</td>
</tr>
<tr>
<td>Lucas Ulmer</td>
</tr>
<tr>
<td>Lakemariam Yohannes</td>
</tr>
<tr>
<td>Worku</td>
</tr>
<tr>
<td>Dien Wu</td>
</tr>
<tr>
<td>Xiaochen Zhu</td>
</tr>
</tbody>
</table>
The Executive Committee has approved the election of the following candidates to the grade of **Associate Member**:

<table>
<thead>
<tr>
<th>Joshua J. Barrett</th>
<th>Brian Horn</th>
<th>Steven L. Marcus</th>
<th>Chad M. Widelo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nicholas Bradford</td>
<td>Daniel D. Inman</td>
<td>Robert Rissland</td>
<td>Casey Winter</td>
</tr>
<tr>
<td>Sherif Gamal Elsharkawy</td>
<td>Edward Jensen</td>
<td>Joe Smith</td>
<td>Keqin Wu</td>
</tr>
</tbody>
</table>

The Executive Committee has approved the election of the following candidates to the grade of **Affiliate Member**:

<table>
<thead>
<tr>
<th>Milind Mujumdar</th>
</tr>
</thead>
</table>

The Executive Committee has approved the election of the following candidates to the grade of **Associate Member—K–12 Teacher**:

<table>
<thead>
<tr>
<th>Kevin Boone</th>
<th>Naomi Herndon</th>
<th>Tami Thomason</th>
<th>Maryalice M. Woody</th>
</tr>
</thead>
</table>

The Executive Committee has approved the election of the following candidates to the grade of **Associate Member—Precollege Student**:

<table>
<thead>
<tr>
<th>Sydney Ann Babbitt</th>
<th>Gunnar M. Consol</th>
<th>Caleb Gossett</th>
<th>Taylor Morton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quinton Beyer</td>
<td>Steven Evans</td>
<td>Riley Ann Laurendine</td>
<td>Simon Murphy</td>
</tr>
<tr>
<td>Stuart Callinan</td>
<td>Jason T. Fogelsonger</td>
<td>Aidan Mahoney</td>
<td>Kevin Vought</td>
</tr>
</tbody>
</table>

**NEW FROM AMS BOOKS!**

**A Scientific Peak: How Boulder Became a World Center for Space and Atmospheric Science**

*Joseph P. Bassi*

> Once a Wild West city tucked between the Rocky Mountains and the Great Plains, Boulder is now home to some of the biggest names in science, including NCAR, NOAA, and NIST.

**Why did big science come to Boulder? How did Boulder become the research mecca it is today?**

*An* *Scientific Peak* is a fascinating history that introduces us to a wide variety of characters, such as Walter Orr Roberts, and the serendipitous brew of politics, passion, and sheer luck that, during the post-WWII and Cold War eras, transformed this “scientific Siberia” into one of America’s smartest cities.

© 2015, 264 pages, paperback
List price: $35  AMS Member price: $25

> bookstore.ametsoc.org
The Executive Committee has approved the election of the following candidates to the grade of Student Member:

- Margot Accettura
- Abhishek Adhikari
- Nikolas O. Aksamit
- Ali Raheem Al-Nassar
- Meshal A. Alrasheed
- Michael Andrew Anand
- Dakari Anderson
- Alex D. Anderson-Connolly
- Seth Antozzi
- Alexandrea J. Arnold
- Carlo Bianchi
- Mitchell K. Black
- Alanna Blanchard
- Katie Boaggio
- Ryan Bolt
- Christopher P. Bossert
- Britanny Broems
- David Buckner
- Eryn M. Cangi
- Forest Cannon
- Tao Cao
- Andrew Caulder
- Joseph X. Cerami
- Kai-Wei Chang
- Anita M. Chavez
- Yu-Cheng Chen
- David D. Chen
- Kai-Yuan Cheng
- Nianliang Cheng
- Peiyang Cheng
- Maksim Cherviakov
- Brett Chrisler
- Emily Churchman
- O. E. Clifton
- Danielle Cohn
- Kevin T. Coldren
- Jason Michael Covert
- Megan Cromis
- Alexandra Culler
- William Cashwa
- Yi Dai
- McKenna J. Davis
- Kevin Delano
- Zachary T. Dennin
- Madeline Rose Diedrichsen
- Zachary Draper
- Avery Duling
- Hanieh Eshagh
- Jason T. Farlow
- Marcos Flores
- Michelle C. Fogarty
- Reid D. Fowler
- Courtney L. Freeman
- Qiang Gao
- Andrew Gardner
- S. M. Iman Gohari
- Jacob J. Graham
- Abigail Haines
- Xuanting Hao
- Brett Harder
- Lindsey A. Hart
- Sarah Harvey
- Manuel Helbig
- Kyle Seewald Hemes
- Eliza Henry
- Julio Enrique Herrera
- Estrada
- Hugh R. Higinbotham
- Janelle Holmes
- Kimberly Holmes
- Yulan Hong
- Michael J. Hosek
- James P. Howard
- Jun Hu
- Alexander Huang
- Chad Hultink
- Jacob Hume
- Laurie Huning
- Kuniaki Inoue
- Pierre-Erik Isabelle
- Allison Jacobel
- Robert D. Jaquette
- Annie Jeckovich
- Jebraiah Thomas Jeffery
- Daniel P. Jensen
- Samantha Johnston
- Jhordanne J. Jones
- Clare Kazanski
- Timothy Benjamin Keebler
- Richard L. Nelson
- Emily Marie Klaus
- Elizabeth Ann Koebele
- Anastasia Korolov
- Sarah A. Kovac
- Yi-Hung Kuo
- Jennifer K. Lake
- Karl Lapo
- Lilian Larson
- Thomas Lavigne
- Kevin D. LeCapitant
- Victoria Levy
- Nana Liu
- Ho Chuan M. Lo
- Lev B. Looney
- Manuel Lopez
- Caroline MacDonald
- Chandler P. MacLaren
- Carl D. Madden
- Derald Madison
- Benjamin Marosites
- Samuel D. Maue
- Brian L. Maxner
- Kevin M. McCarthy
- Jessa R. McGaha
- William A. McNichols
- Caitlyn Mensch
- Ashley Victoria Merzon
- Justine Missik
- Ali Jasim Mohammed
- Mostafa Momen
- Laura J. Moon
- Elizabeth Morehead
- Daniel Mukibi
- Ian Murray
- Hafsaah Nahrawi
- Husain Najafi
- Sara M. Noble
- Christopher Noyes
- Brendan M. O’Connor
- Gun Ho Oh
- Sophie Orendorf
- Bonnie Jean Owen
- Roshani Pahari
- May A. Palace
- John A. Pavacic
- Amanda Penning
- Stephanie Pennington
- Bill Peria
- David C. Piatt
- Arron R. Potter
- Justin Puckett
- Hongchen Qin
- Jamin Rader
- Jonathan Radford
- Bharat Rastogi
- Chinthaka Ravinatha
- Stephanie H. Reeves
- Mike Rehnberg
- Devin Remington
- Zachary Austin Rhoads
- Alex P. Rickel
- David J. Riviera
- Shawn C. Roj
- Zoey Rosen
- Karen Lee Russ
- Cameron Saliga
- Kyle Sanchez
- Gilmarie Santos-Figueroa
- Daniel P. Sarmiento
- Zane Keil Satre
- Joshua J. Sefcik
- Jonathan J. Seibert
- Anja Sendelbeck
- Sanjib Sharma
- Shawn W. Simmons
- Mary E. Spraggs
- Zachary Ryan Stanford
- Sheena Marie Steffen
- Jacob Strohm
- Kyle Stropes
- Xuezhi Tan
- Shuai Tang
- Brandon M. Thacker
- Matthew Thigpen
- Megan Varcie
- Randall Vowles
- Yuntao Wang
- Robert Dale Travis Wendt
- Luke M. Western
- Caleb Wood
- Lichuan Wu
- Ross J. Wusterbarth
- Ke Xu
- Anqing Xuan
- Jian Yang
- Aara’L Yarbar
- Chau Lam Yu
- Brianna Zawadzki
- Xiaowei Zhu
- Brad Zylstra
An exhibit program will be held at this meeting.

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

#### 2016

**NOVEMBER**

28th Conference on Severe Local Storms, 7–11 November, Portland, Oregon
- Abstract deadline: 7 July 2016
- Preregistration deadline: 1 October 2016
- Manuscript deadline: 7 December 2016

#### JANUARY

16th Annual AMS Student Conference, 21–22 January, Seattle, Washington
- Abstract deadline: 3 October 2016
- Preregistration deadline: 15 December 2016

AMS Short Course: A Beginner’s Course to Using Python in Climate and Meteorology, 21–22 January, Seattle, Washington
- Preregistration deadline: 1 December 2016

GIS Tutorial for Atmospheric Sciences, 21–22 January, Seattle, Washington
- Preregistration deadline: 1 December 2016

Experiencing JPSS Capabilities, 21 January, Seattle, Washington
- Preregistration deadline: 1 December 2016

AMS Short Course on Environmental Security, 22 January, Seattle, Washington
- Preregistration deadline: 1 December 2016

GOES-R Preview for all GOES Users, 22 January, Seattle, Washington
- Preregistration deadline: 1 December 2016

AMS Short Course on Environmental Security, 22 January, Seattle, Washington
- Preregistration deadline: 1 December 2016

AMS Short Course: Cloud-based Data Exploration and Machine Learning on Environmental Datasets, 22 January, Seattle, Washington
- Preregistration deadline: 1 December 2016

AMS Short Course on Interacting with Radar Data in the Cloud, 22 January, Seattle, Washington
- Preregistration deadline: 1 December 2016

Fifth Annual AMS Conference for Early Career Professionals, 22 January, Seattle, Washington
- Preregistration deadline: 15 December 2016
- Initial announcement published: June 2016

- Preregistration deadline: 1 December 2016

- Abstract deadline: 1 August 2016
- Preregistration deadline: 1 December 2016
- Manuscript deadline: 27 February 2017
- Initial announcement published: May 2016

*Special Symposium on Individual, Social, and Cultural Observations in Weather and Climate Contexts, 22–26 January, Seattle, Washington
- Abstract deadline: 1 August 2016
- Preregistration deadline: 1 December 2016
- Manuscript deadline: 27 February 2017
- Initial announcement published: May 2016

*Lance Bosart Symposium, 22–26 January, Seattle, Washington
- Abstract deadline: 1 August 2016
- Preregistration deadline: 1 December 2016
- Manuscript deadline: 27 February 2017
- Initial announcement published: April 2016

- Abstract deadline: 1 August 2016
- Preregistration deadline: 1 December 2016
- Manuscript deadline: 27 February 2017

*An exhibit program will be held at this meeting.
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: April 2016

*29th Conference on Climate Variability and Change, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: May 2016

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: April 2016

*18th Conference on Aviation, Range, and Aerospace Meteorology, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: March 2016

*15th Conference on Artificial and Computational Intelligence and its Applications to the Environmental Sciences, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: May 2016

*15th History Symposium, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

*15th Symposium on the Coastal Environment, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

* An exhibit program will be held at this meeting.

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**STUDENT TRAVEL GRANTS**

Student Travel Grants are available for senior undergraduate and graduate students to attend AMS meetings held in the United States and Canada. The travel grants are available only to members, including student members, of the AMS.

AMS recognizes the considerable benefit that students can gain from attending conferences even if they are not presenting a paper there, and AMS wants to encourage interactions between students and other conference attendees. To this end, travel grants will be awarded to a student who is not presenting a paper at the conference.

Students who are presenting papers and potentially in need of travel support should inquire of the program chair whether any funds will be available for this purpose.

For more information and to complete an application form, please visit the AMS website at www.ametsoc.org.
*14th Conference on Polar Meteorology and Oceanography, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: May 2016

*14th Conference on Space Weather, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: May 2016

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: April 2016

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: April 2016

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: April 2016

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

*Seventh Conference on Transition of Research to Operations, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: April 2016

*Fifth Symposium on Aerosol–Cloud–Climate Interactions, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017
Initial announcement published: April 2016

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

*Seventh Symposium on Advances in Modeling and Analysis Using Python, 22–26 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

*Second Symposium on Multi-Scale Atmospheric Predictability, 25 January, Seattle, Washington
Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

Abstract deadline: 1 August 2016
Preregistration deadline: 1 December 2016
Manuscript deadline: 27 February 2017

*An exhibit program will be held at this meeting.
**Special Symposium on Severe Local Storms: Observation Needs to Advance Research, Prediction, and Communication, 24 January, Seattle, Washington**  
Abstract deadline: 1 August 2016  
Preregistration deadline: 1 December 2016  
Manuscript deadline: 27 February 2017  
Initial announcement published: May 2016

**Special Symposium on Greening the Built Environment, 26 January, Seattle, Washington**  
Abstract deadline: 1 August 2016  
Preregistration deadline: 1 December 2016  
Manuscript deadline: 27 February 2017  
Initial announcement published: May 2016

**Special Symposium on Meteorological Observations and Instrumentation, 22–26 January, Seattle, Washington**  
Abstract deadline: 1 August 2016  
Preregistration deadline: 1 December 2016  
Manuscript deadline: 27 February 2017  
Initial announcement published: May 2016

**45th Conference on Broadcast Meteorology, 21–23 June, Kansas City, Missouri**  
Abstract deadline: 14 February 2017  
Preregistration deadline: 10 May 2017  
Manuscript deadline: 19 July 2017  

**Fourth Conference on Weather Warnings and Communication, 21–23 June, Kansas City, Missouri**  
Abstract deadline: 14 February 2017  
Preregistration deadline: 10 May 2017  
Manuscript deadline: 19 July 2017  
Initial announcement published: TBD

**21st Conference on Atmospheric and Oceanic Fluid Dynamics, 26–30 June, Portland, Oregon**  
Abstract deadline: 1 March 2017  
Preregistration deadline: 19 May 2017  
Manuscript deadline: 26 July 2017  

<table>
<thead>
<tr>
<th>MEETINGS OF INTEREST</th>
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</thead>
<tbody>
<tr>
<td><strong>OCTOBER</strong></td>
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<tr>
<td>Sixth Tri-State Weather Conference, 1 October, Danbury, Connecticut</td>
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<tr>
<td>NOAA’s 41st Climate Diagnostics and Prediction Workshop, 3–6 October, Orono, Maine</td>
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<tr>
<td>A Connected Ocean (ACO)/The Challenge of Observation Data Integration, 11–13 October, Brest, France</td>
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<tr>
<td>Convective and Volcanic Clouds Detection, Monitoring and Modeling, 19–28 October, Tarquinia, Italy</td>
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<tr>
<td><strong>FEBRUARY</strong></td>
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<tr>
<td>Fourth Santa Fe Conference on Global &amp; Regional Climate Change 5–10 February, Santa Fe, New Mexico</td>
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<td><strong>APRIL</strong></td>
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<tr>
<td>International Conference on Mountain Hydrology and Meteorology for Sustainable Development, 10–11 April, Kathmandu, Nepal</td>
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<tr>
<td>Second European Hail Workshop, 19–21 April, Bern, Switzerland</td>
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<tr>
<td>EGU 2017 General Assembly, 23–28 April, Vienna, Austria</td>
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<tr>
<td><strong>JUNE</strong></td>
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<tr>
<td>Fifth International Symposium on Atmospheric Light Scattering and Remote Sensing, 19–23 June, Hefei, China</td>
</tr>
</tbody>
</table>

*An exhibit program will be held at this meeting.*
HURRICANE PIONEER
Memoirs of Bob Simpson
Robert H. Simpson with Neal M. Dorst

In 1951, Bob Simpson rode a plane directly into the wall of a hurricane—just one of his many pioneering explorations. This autobiography of the first director of the National Hurricane Research Project and co-creator of the Saffir-Simpson Hurricane Scale starts with childhood remembrance and ends in first-hand account of a revolutionary...

© 2014, PAPERBACK
ISBN: 978-1-935704-75-1
LIST $30 MEMBER $20

AN OBSERVER’S GUIDE TO CLOUDS AND WEATHER
A Northeast Primer on Prediction
Toby Carlson, Paul Knight, and Celia Wyckoff

With help from Penn State experts, start at the beginning and go deep. This primer for enthusiasts and new students alike will leave you with both refined observation skills and an understanding of the complex science behind the weather: the ingredients for making reliable predictions of your own.

© 2014, PAPERBACK
LIST $35 MEMBER $20

CLIMATE CONUNDRUMS
What the Climate Debate Reveals About Us
William B. Gail

This is a journey through how we think, individually and collectively, derived from the climate change debate. With wit and wisdom, Gail explores several questions: Can we make nature better? Could science and religion reconcile? Insights from such issues can help us better understand who we are and help...

© 2014, PAPERBACK
ISBN: 978-1-935704-74-4
LIST $30 MEMBER $20
Our ability to observe the atmosphere, hydrosphere, lithosphere, and cryosphere underlies our understanding of the Earth system and our ability to predict its evolution. The richness of Earth system observations enables us to span disciplinary boundaries to make exciting discoveries about our planet and address challenges to human health, food security, sustainable energy, water quality and abundance, and environmental change. This year’s Presidential Forum will include presentations and discussion about how our current observations serve societal needs and the limitations, vulnerabilities, and requirements for our future Earth observing system.

The panel comprises five preeminent researchers:

- Dr. Vanda Grubišić, moderator, National Center for Atmospheric Research (NCAR) senior scientist and associate director for the Earth Observing Laboratory;
- Professor Richard Jackson, University of California, Los Angeles, and former director of the Center for Disease Control’s (CDC) National Center for Environmental Health;
- Professor Andrew Light, George Mason University, distinguished senior fellow in the climate program at the World Resources Institute, and former U.S. Department of State senior climate change official;
- Professor Don Wuebbles, University of Illinois at Champaign–Urbana, and assistant director, climate science, White House Office of Science and Technology Policy; and
- Dr. Roger Pulwarty, National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory, senior science advisor for climate, and the director of the National Integrated Drought Information System (NIDIS).

The forum will address the following topics:

- Earth system observation requirements for human health;
- agreements from the 2015 United Nations Climate Change Conference (COP21) and the role of observations in “trust and verify”;
- greenhouse gas monitoring and the future Earth observing system: challenges and opportunities; and
- Earth system observations at the nexus of food, energy, and water.

In addition to the high-level perspectives provided in the Presidential Forum, the 2017 theme of “Observations Lead the Way” permeates throughout the AMS Annual Meeting. There will be two invited-speaker symposia: “Observation symposium: Progress, problems, and prospects” and “Special symposium on individual, social, and cultural observations in weather and climate contexts”, with the latter exploring contributions the social sciences can provide to the atmospheric sciences community. There are also several other conferences/symposia dedicated solely to observations. Moreover, nearly all other conferences/symposia will have designated themed joint sessions or keynote talks on the critical observational requirements for their disciplines. All recommendations for crucial observations or instruments made in any session during the AMS Annual Meeting will be captured and summarized in a future BAMS article on the “community consensus” for vital environmental measurements.

For additional information, please contact Chris Davis (e-mail: cdavis@ucar.edu). (10/16)
the demonstration of a practical case study. This short course also describes the development of small, affordable unmanned systems, to expand the understanding of atmospheric conditions and improve weather forecasting, as well as to fundamentally demonstrate the value of using small unmanned aircraft to monitor and investigate the lower atmosphere.

Please join us for this short course designed to introduce and discuss all aspects of setting up, deploying, and operating a meteorological mesoscale network. Well over a dozen states have some form of a mesonet already in place, providing critical real-time weather information to a variety of sectors, including emergency management, agriculture, utilities, and transportation, among others. Yet these networks are amazingly complex. This short course will introduce many of the steps involved in setting up and operating a large-scale network. Topics will include network design, station siting and permitting, station configuration, sensor selection, power, communications, data quality control, and network operations.

The instructors for the course are C. H. (Chester) Huang, Ph.D., CCM (Organize); Prof. Jerald Brotzge; Prof. Dr. Stefan Emeis; Zhiquan (Jake) Liu, Ph.D.; and Phillip B. Chilson, PhD. Participants are encouraged to bring their laptops or tablets for the hands-on exercises.

For more information, please contact Chester Huang (e-mail: chester.huang@boem.gov). (10/16)

CALL FOR PAPERS

45th Conference on Broadcast Meteorology, 21–23 June 2017, Kansas City, Missouri

The 45th Conference on Broadcast Meteorology, sponsored by the American Meteorological Society, returns to the central United States to the BBQ capital! The conference will be held at the Intercontinental Hotel in Kansas City, Missouri, on 21–23 June 2017, with a short course on 20 June 2017. This location will serve as both the conference meeting destination and the designated hotel accommodation, conveniently located about 4 miles south of downtown Kansas City on the historic Country Club Plaza. The closest airport is Kansas City International (MCI), located about 18 miles north of the Intercontinental. Basic hotel and travel information is available on the AMS website (www.ametsoc.org).

As with every year, we encourage presentations that focus on recent weather events and weather phenomena that are unique to our host region. As broadcasters, we encourage broadcaster presentations, showcasing how science is communicated across the country. Student presentations are also welcome. Below are some suggested areas we hope to delve into during this year’s conference.

Tension remains between how weather events are communicated on a local broadcast scale versus the national weather headlines. How can local weather stories be better told (accurately and without undue sensationalism) at the network level? How can national news outlets better tap into the local knowledge of market broadcast meteorologists? What are wise ways to accurately inform reporters (both local and national) about the context of weather events? How can local competing stations prevent “first on, last off” viewership battles and cover local weather events in a balanced and appropriate manner to best serve the communities who depend on us?

As the way science is communicated continues to evolve with technology and social media platforms, we particularly encourage presentations related to social media. How do we regulate, filter, and validate the dissemination of weather information across social media platforms? Can social media help lower warning false alarm rates by providing more spotter reports in real time? With the whiplash-changing landscape of social media, how do broadcast meteorologists keep up with platforms, select the most beneficial ones, utilize them effectively, and track analytics? Case studies and examples of successful social media weather stories are encouraged.

National conversations about racism, ageism, and sexism continue. Discrimination is also within broadcast television. How do we in broadcasting appropriately identify cases of discrimination and also encourage diverse and inclusive workplaces? How are employers meeting the legal needs and rights of new parents, both nursing mothers and new fathers? How can television stations better value meteorology experience, knowledge, and wisdom? What are great examples of broadcast companies and local affiliates that provide for and encourage a healthy work balance in a 24/7 field? We welcome broadcasters’ stories and human resource presentations regarding these important national topics.

We also encourage presentations on companion fields of science, including connections with social science, climate science, oceanography, agriculture, astronomy, and space weather. More details on the conference program and the short course will appear on the AMS website by mid-March 2017.

The deadline for abstracts is 14 February 2017. An abstract fee of $95 (payable by credit card or purchase order) is charged at the time of submission (refundable only if abstract is not accepted). The abstract fee includes the submission of your abstract, the posting of your extended abstract, and the uploading and recording of your presentation that will be archived on the AMS website. Authors of accepted presentations will be notified via e-mail mid-March.
CALL FOR PAPERS


The 17th Conference on Mesoscale Processes, sponsored by the AMS and organized by the AMS Committee on Mesoscale Processes, will be held on 24–28 July 2017 at the Crowne Plaza Hotel in San Diego, California. A preliminary conference program, along with hotel and registration information, will be posted on the AMS website (www.ametsoc.org) by mid-May 2017.

Oral and poster presentations are solicited on all aspects of mesoscale meteorology, which include but are not limited to observational, theoretical, and modeling climate and weather-related studies of the following:

- mesoscale convection;
- mesoscale predictability;
- gravity waves and turbulence;
- orographic flows and rainfall;
- extratropical and tropical cyclones;
- the diurnal cycle; and
- microphysical and aerosol effects on mesoscale processes.

Papers on 1) mesoscale processes in climate simulations, 2) the use of data assimilation and ensemble forecasting to enhance predictability, and 3) results from recent field campaigns (e.g., DEEPWAVE, DYNAMO, MPEX, OWLeS, PECAN) are especially encouraged.

The Mesoscale Processes Committee encourages abstract submissions from students and postdocs for which awards will be given for best presentations. Registrants should indicate their eligibility for student and postdoc awards when submitting their abstracts. Further information will be posted on the conference webpage (www.ametsoc.org/ams/index.cfm/meetings-events/ams-meetings/17th-conference-on-mesoscale-processes/).

The Mesoscale Processes Committee is also offering three student travel awards to help supplement travel expenses. To be eligible for a travel award, the student must be a current AMS student member, not be a resident of San Diego, and have submitted an abstract for presentation at the meeting. To apply, please send your CV and a brief (½ page) justification to the program chairpersons (contact information located at the end) by the abstract deadline of 30 March 2017. Further information can be found on the AMS website (www.ametsoc.org/ams/index.cfm/meetings-events/ams-meetings/17th-conference-on-mesoscale-processes/student-opportunities/).

Multiple submissions are allowed by individual authors. However, AMS policy limits participation to one oral presentation each (please note that additional submissions will be assigned as posters). The availability of oral presentations, however, will depend on the number of submissions. When submitting more than one abstract, authors are also asked to specify which abstract they would prefer to be considered for oral presentation. Abstracts should be submitted online (http://ams.confex.com/ams) by the deadline of 30 March 2017. An abstract fee of $95.00 (payable by credit card or purchase order) is required at the time of abstract submission (refundable only if abstract is not accepted). This fee includes the posting of your abstract and the posting of your presentation and its recording (if consented to) on the AMS website.

Authors of accepted presentations will be notified via e-mail by late April 2017. Extended abstracts (file size limit of 10 mb) must be submitted electronically by 22 August 2017 and will be posted on the AMS website. Instructions for formatting these optional extended abstracts will be posted on the AMS website. All abstracts, extended abstracts, and presentations (including the recordings of those who have granted permission) will be made available on the AMS website.

For further information, please contact the conference co-chairs: Katja Friedrich (e-mail: katja.friedrich@colorado.edu) or Stan Trier (e-mail: trier@ucar.edu). (10/16)
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: A Collection of Essays in Honor of David Atlas

Price $80.00 member

To place an order point your Web browser to www.ametsoc.org/amsbookstore

AMS BOOKS
RESEARCH ▶ APPLICATIONS ▶ HISTORY
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.

### 2017 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 2017 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

**HYDROLOGIC RESEARCH AWARDS COMMITTEE**
- Hydrologic Sciences Medal

**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 Edward N. Lorenz Teaching Excellence Award
- Distinguished Science Journalism in the Atmospheric and Related Sciences

**PROFESSIONAL AFFAIRS COMMISSION**
- Outstanding Contribution to the Advance of Applied Meteorology
- Award for Broadcast Meteorology
- Award for Excellence in Science Reporting by a Broadcast Meteorologist
- The Henry T. Harrison Award for Outstanding Contributions by a Consulting Meteorologist

**WEATHER AND CLIMATE ENTERPRISE COMMISSION**
- The Kenneth C. Spengler Award

**LOCAL CHAPTER AFFAIRS COMMITTEE**
- Local Chapter of the Year Award

*Recommended by the Atmospheric Research Awards Committee in even-numbered years and by the Oceanographic Research Awards Committee in odd-numbered years.*
2017 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
  Robert E. Horton Lecturer in Hydrology
  Bernhard Haurwitz Memorial Lecturer
  Walter Orr Roberts Lecturer

• PAPER
  Banner I. Miller

• STUDENT PAPERS
  Robert Leviton Student Prize
  Max A. Eaton Student Prize
  Spiros G. Geotis Student Prize
  Peter V. Hobbs Student Prize

• 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…

2017 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 2017. A list of Fellows and the process for submitting nominations are on the AMS website (www.ametsoc.org/awards).

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 Annual Meeting and 2) four positions on the Council for a term of three years starting at the close of the Annual Meeting.

As per Article VI of the AMS Constitution, formal nominations by petition may be submitted to the Secretary-Treasurer by 1 July. In addition, the AMS Nominating Committee welcomes recommendations from the membership of candidates for office, which will be considered as the slate is prepared. Such recommendations will be most helpful if they are sent to the Nominating Committee nominating-committee@ametsoc.org by the end of December and are in the form of a 1-page letter describing the proposed candidate’s background and qualifications. Questions about the nomination process should also be addressed 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 2017; a form and list of Honorary Members is available at www.ametsoc.org/awards.
CORPORATION AND INSTITUTIONAL MEMBERS

Membership in the American Meteorological Society does not imply AMS endorsement of an organization’s products or services.

SUSTAINING MEMBERS
Ball Aerospace & Technologies Corporation
Harris Corporation
Lockheed Martin Corporation
Northrop Grumman Corporation
The Weather Channel
University Corporation for Atmospheric Research
Vaisala, Inc.

REGULAR MEMBERS
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Advances in Atmospheric Sciences
Aerospace & Marine International Corporation
Amazon Web Services, Inc.
Atmospheric and Environmental Research, Inc.
Atmospheric Technology Services Company, LLC
Baron Services, Inc.
Botswana Meteorological Services
Campbell Scientific, Inc.
CLS America, Inc.
CSIRO Marine and Atmospheric Research
Davis Instruments Corporation
EKO Instruments Company, Ltd.
Enterprise Electronics Corporation
Environmental Systems Research, Inc.
ERT, Inc.
Global Science & Technology, Inc.
Global Weather Corporation
Johns Hopkins University, Applied Physics Laboratory
Kipp & Zonen USA Inc.
Meteorological Technology International
Murray & Trettel, Inc.
NOAA Office for Coastal Management
Orbital ATK, Inc.
Panasonic Weather Solutions
Pelmorex Media Inc.
ProSensing, Inc.
Radiometrics Corporation
R. M. Young Company
Riverside Technology, inc.
Royal Netherlands Meteorological Institute
Schneider Electric Weather
Science Applications International Corporation
Science Systems and Applications, Inc.
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SeaSpace Corporation
SGT, Inc.
Sonalytics, Inc.
SpectraSensors, Inc.
Sutron Corporation
The Aerospace Corporation
U.S. Department of Energy, Office of Science
Unisys Corporation
University of Alabama in Huntsville, Earth System Science Ctr
University of Illinois, Department of Atmospheric Sciences
University of Oklahoma, School of Meteorology
University of Wisconsin—Madison, SSEC
Vieux, Inc.
Weather Decision Technologies
Weather Modification, Inc.
Weather Services International, Inc.

SMALL BUSINESS MEMBERS
EWR Weather Radar Systems
Geonor, Inc.
National Council of Industrial Meteorologists
National Weather Service Employees Organization
Remtech, Inc.
WeatherSTEM, Inc.
Yankee Environment Systems, Inc.

PUBLICATIONS MEMBERS
557th Weather Wing (USAF)
Abdus Salam International Centre for Theoretical Physics
ARPA FVG, Osservatorio Meteorologico Regionale
Bureau of Meteorology
Civil Aeronautics Administration, MOTC
CNR
Colorado State University Libraries
Columbia University, Lamont-Doherty Geological Observatory
Dartmouth College Baker Library
Desert Research Institute
Deutscher Wetterdienst
Embry Riddle Aeronautical University
Environment Canada Library, Downsview
EUMETSAT Library
Finnish Meteorological Institute
Florida International University Library
Geophysical Institute/International Arctic Research Center
Harvard University, Gordon McKay and Blue Hill Libraries
Hong Kong Observatory Library
Indian Institute of Technology Bhubaneswar

For questions relating to corporation and institutional membership, please contact Maria Sarantopoulos at AMS Headquarters—telephone: 617-227-2426, x3912; fax: 617-742-8718; e-mail: msarantopoulos@ametsoc.org; or write to American Meteorological Society, Attn: Maria Sarantopoulos, 45 Beacon St., Boston, MA 02108-3693.
CORPORATION AND INSTITUTIONAL MEMBERS

Indian Institute of Tropical Meteorology
India Meteorological Department
Indiana University Library
Irish Meteorological Service
Japan Weather Association
Los Alamos National Laboratory
Lyndon State College, Samuel Read Hall Library
MBL/WHOI Library
Meteo-France
Meteorological Service of New Zealand Ltd.
MeteoSwiss
Meteorologisk institutt
Millersville University, Department of Earth Sciences
MIT, Lincoln Laboratory
National Centers for Environmental Information
National Environment Agency
National Weather Center Library
Naval Postgraduate School, Dudley Knox Library
New York University
NIWA Wellington Library
NOAA - GLERL Library
NOAA AOML Library
NOAA Central Library
NOAA Seattle Library
North Carolina State University Hunt Library
Pennsylvania State University, Paterno Library
Republic of Korea Air Force, Headquarters
South African Weather Service
St. Louis University, Dept. of Earth & Atmospheric Sciences
Swedish Meteorological & Hydrological Institute
The University Centre in Svalbard
U.K. National Meteorological Library
U.S. Army Corps of Engineers, Library - ERDC
U.S. Department of Commerce, Boulder Labs Library
U.S. EPA Main Library
Universitatsbibliothek Innsbruck
Universitätsbibliothek Trier
University of Colorado Libraries
University of Copenhagen, Niels Bohr Institute Library
University of Delaware Library
University of Frankfurt Library
University of Hawaii at Manoa, Library
University of Maryland, McKeldin Library
University of Melbourne, Baillieu Library
University of New South Wales Library
University of North Carolina, Ramsey Library
University of North Dakota, Chester Fritz Library
University of Northern Colorado, Michener Library
University of Washington Libraries
WeatherPredict Consulting Inc.
Weizmann Institute of Science
Yale University, Center for Science & Social Science Info.
Zentralanstalt fur Meteorologie und Geodynamik

Color indicates new or reinstated member
FELLOWSHIPS
AMS Giving Program
DOE, Atmospheric System Research
Lockheed Martin Corporation*
NASA Earth Science
NOAA’s Climate Program Office
NOAA’s National Weather Service

FRESHMAN AND UNDERGRADUATE SCHOLARSHIPS
Baron Services Inc.
Earth Networks
CLS America, Inc.
Harris Corporation
Lockheed Martin MS2
Naval Weather Service Association
Raytheon Company
R. M. Young Company
SAIC, Center for Atmospheric Physics
Science and Technology Corporation
Stinger Ghaffarian Technologies
Vaisala, Inc.
Jerome Namias Memorial Endowed Scholarship
Edgar J. Saltsman Endowed Scholarship
Bernard Vonnegut and Vincent Schaefer Endowed Scholarship
Percival D. Wark and Clara B. (Mackey) Wark Endowed Scholarship

MINORITY SCHOLARSHIPS
AMS Giving Program

SENIOR SCHOLARSHIPS
AMS 75th Anniversary Endowed Scholarship
Bhanwar Lal Bahethi Scholarship
Om and Saraswati Bahethi Scholarship
Saraswati (Sara) Bahethi Scholarship
Werner A. Baum Undergraduate Endowed Scholarship
Loren W. Crow Memorial Scholarship
The Dr. Robert Fraser Scholarship
Karen Hauschild Friday Endowed Scholarship
Bob Glahn Endowed Scholarship in Statistical Meteorology
The Jerry C. Glover Scholarship
Dr. Pedro Grau Undergraduate Scholarship
Richard and Helen Hagemeyer Scholarship
John R. Hope Endowed Scholarship in Atmospheric Sciences
David S. Johnson Endowed Scholarship
Larry R. Johnson Scholarship
Dr. Yoram Kaufman Scholarship
Carl W. Kreitzberg Endowed Scholarship
Ethan and Allan Murphy Endowed Memorial Scholarship
The Naval Weather Service Association Scholarship Award
K. Vic Ooyama Endowed Scholarship
The Orville Family Endowed Scholarship in Meteorology
The Ken Reeves Scholarship
Michael J. Roberts, Jr. Scholarship
Guillermo Salazar Rodriguez Undergraduate Scholarship
Mark J. Schroeder Endowed Scholarship in Meteorology

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AMERICAN METEOROLOGICAL SOCIETY

AUDITED FINANCIAL STATEMENTS
AND SUPPLEMENTARY INFORMATION

DECEMBER 31, 2015
INDEPENDENT AUDITORS REPORT

TO THE EXECUTIVE COMMITTEE
AMERICAN METEOROLOGICAL SOCIETY
Boston, Massachusetts

Report on the Financial Statements

We have audited the accompanying financial statements of American Meteorological Society which comprise the statement of financial position as of December 31, 2015, and the related statements of activities, changes in net assets, and cash flows for the year then ended, and the related notes to the financial statements.

Management’s Responsibility for the Financial Statements

Management is responsible for the preparation and fair presentation of these financial statements in accordance with accounting principles generally accepted in the United States of America; this includes the design, implementation, and maintenance of internal control relevant to the preparation and fair presentation of financial statements that are free from material misstatement, whether due to fraud or error.

Auditor’s Responsibility

Our responsibility is to express an opinion on these financial statements based on our audit. We conducted our audit in accordance with auditing standards generally accepted in the United States of America and the standards applicable to financial audits contained in Government Auditing Standards, issued by the Comptroller General of the United States. Those standards require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free from material misstatement.

An audit involves performing procedures to obtain audit evidence about the amounts and disclosures in the financial statements. The procedures selected depend on the auditor’s judgment, including the assessment of the risks of material misstatement of the financial statements, whether due to fraud or error. In making those risk assessments, the auditor considers internal control relevant to the entity’s preparation and fair presentation of the financial statements in order to design audit procedures that are appropriate in the circumstances, but not for the purpose of expressing an opinion on the effectiveness of the entity’s internal control. Accordingly, we express no such opinion. An audit also includes evaluating the appropriateness of accounting policies used and the reasonableness of significant accounting estimates made by management, as well as evaluating the overall presentation of the financial statements.

We believe that the audit evidence we have obtained is sufficient and appropriate to provide a basis for our audit opinion.

Opinion

In our opinion, the financial statements referred to above present fairly, in all material respects, the financial position of American Meteorological Society as of December 31, 2015, and the changes in its net assets and its cash flows for the year then ended in accordance with accounting principles generally accepted in the United States of America.
Other Matters

Other Information

Our audit was conducted for the purpose of forming an opinion on the financial statements as a whole. The accompanying schedule of expenditures of federal awards, as required by Title 2 U.S. Code of Federal Regulations (CFR) Part 200, Uniform Administrative Requirements, Cost Principles, and Audit Requirements for Federal Awards, is presented for the purposes of additional analysis and is not a required part of the financial statements. The accompanying schedule of net assets by restriction is presented for purposes of supplementary analysis and is also not a required part of the financial statements. Such information is the responsibility of management and was derived from and relates directly to the underlying accounting and other records used to prepare the financial statements. The information has been subjected to the auditing procedures applied in the audit of the financial statements and certain additional procedures, including comparing and reconciling such information directly to the underlying accounting and other records used to prepare the financial statements or to the financial statements themselves, and other additional procedures in accordance with auditing standards generally accepted in the United States of America. In our opinion, the information is fairly stated in all material respects in relation to the financial statements as a whole.

Other Reporting Required by Government Auditing Standards

In accordance with Government Auditing Standards, we have also issued our report dated August 1, 2016, on our consideration of American Meteorological Society’s internal control over financial reporting and on our tests of its compliance with certain provisions of laws, regulations, contracts, and grant agreements and other matters. The purpose of that report is to describe the scope of our testing of internal control over financial reporting and compliance and the results of that testing, and not to provide an opinion on internal control over financial reporting or on compliance. That report is an integral part of an audit performed in accordance with Government Auditing Standards in considering American Meteorological Society’s internal control over financial reporting and compliance.

Tonnesson & Company PC
Burlington, Massachusetts
August 1, 2016
### STATEMENT OF FINANCIAL POSITION
#### DECEMBER 31, 2015

**Assets**

**Current Assets:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cash</td>
<td>$1,080,783</td>
</tr>
<tr>
<td>Accounts receivable from members, subscribers and others</td>
<td>10,459</td>
</tr>
<tr>
<td>Short-term investments</td>
<td>8,196,593</td>
</tr>
<tr>
<td>Prepaid expenses and other current assets</td>
<td>1,334,215</td>
</tr>
<tr>
<td>Inventory</td>
<td>174,891</td>
</tr>
<tr>
<td><strong>Total Current Assets</strong></td>
<td><strong>10,796,941</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property and Equipment</td>
<td>11,487,274</td>
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**Other Assets:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term investments</td>
<td>549,642</td>
</tr>
<tr>
<td><strong>Total Assets</strong></td>
<td><strong>$22,833,857</strong></td>
</tr>
</tbody>
</table>

**Liabilities and Net Assets**

**Current Liabilities:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bank line of credit</td>
<td>$500,000</td>
</tr>
<tr>
<td>Current portion of long-term debt</td>
<td>183,333</td>
</tr>
<tr>
<td>Accounts payable and accrued expenses</td>
<td>561,999</td>
</tr>
<tr>
<td>Deferred income</td>
<td>3,915,835</td>
</tr>
<tr>
<td><strong>Total Current Liabilities</strong></td>
<td><strong>5,161,167</strong></td>
</tr>
</tbody>
</table>

**Long-Term Liabilities:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charitable gift annuity liability</td>
<td>152,651</td>
</tr>
<tr>
<td>Fair value of interest rate swap agreement</td>
<td>224,195</td>
</tr>
<tr>
<td>Long-term debt, net of current portion</td>
<td>4,384,722</td>
</tr>
<tr>
<td>Commitments</td>
<td>—</td>
</tr>
<tr>
<td><strong>Total Long-Term Liabilities</strong></td>
<td><strong>4,761,568</strong></td>
</tr>
</tbody>
</table>

**Total Liabilities**

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Liabilities</strong></td>
<td><strong>9,922,735</strong></td>
</tr>
</tbody>
</table>

**Net Assets**

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unrestricted</td>
<td>10,523,223</td>
</tr>
<tr>
<td>Temporarily restricted</td>
<td>1,745,196</td>
</tr>
<tr>
<td>Permanently restricted</td>
<td>642,703</td>
</tr>
<tr>
<td><strong>Total Net Assets</strong></td>
<td><strong>12,911,122</strong></td>
</tr>
</tbody>
</table>

**Total Liabilities and Net Assets**

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Liabilities and Net Assets</strong></td>
<td><strong>$22,833,857</strong></td>
</tr>
</tbody>
</table>

The accompanying notes are an integral part of the financial statements.
### Unrestricted Net Assets:

**Revenues, Gains and Other Support:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Publications</td>
<td>$7,995,664</td>
</tr>
<tr>
<td>Meetings and exhibits</td>
<td>3,313,821</td>
</tr>
<tr>
<td>Membership and communication</td>
<td>2,049,159</td>
</tr>
<tr>
<td>Other educational assistance</td>
<td>1,702,345</td>
</tr>
<tr>
<td>Federal financial assistance</td>
<td>1,233,707</td>
</tr>
<tr>
<td>Investment income</td>
<td>152,157</td>
</tr>
<tr>
<td>Other contributions</td>
<td>79,750</td>
</tr>
<tr>
<td>Net assets released from restrictions</td>
<td>70,932</td>
</tr>
<tr>
<td>Realized and unrealized (losses) on investments</td>
<td>(198,628)</td>
</tr>
<tr>
<td>Unrealized gain on interest rate swap agreement</td>
<td>16,507</td>
</tr>
</tbody>
</table>

Total: $16,415,414

**Expenses:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program services:</td>
<td></td>
</tr>
<tr>
<td>Publications</td>
<td>7,392,473</td>
</tr>
<tr>
<td>Education and policy programs</td>
<td>4,013,590</td>
</tr>
<tr>
<td>Meetings and exhibits</td>
<td>3,212,042</td>
</tr>
<tr>
<td>Membership and communication</td>
<td>2,546,324</td>
</tr>
<tr>
<td>Supporting services:</td>
<td></td>
</tr>
<tr>
<td>Administrative and general</td>
<td>471,824</td>
</tr>
<tr>
<td>Interest expense</td>
<td>176,734</td>
</tr>
</tbody>
</table>

Total: $17,812,987

*(Decrease) in Unrestricted Net Assets* (1,397,573)

### Temporarily Restricted Net Assets:

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contributions</td>
<td>63,489</td>
</tr>
<tr>
<td>Investment income</td>
<td>19,923</td>
</tr>
<tr>
<td>Net assets released from restrictions</td>
<td>(70,932)</td>
</tr>
<tr>
<td>Realized and unrealized (losses) on investments</td>
<td>(10,268)</td>
</tr>
</tbody>
</table>

Increase in Temporarily Restricted Net Assets 2,212

### Permanently Restricted Net Assets:

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment income</td>
<td>1</td>
</tr>
</tbody>
</table>

Increase in Permanently Restricted Net Assets 1

*(Decrease) in Net Assets* (1,395,360)

Net assets at beginning of year 14,306,482

**Net Assets at End of Year** $12,911,122

---

The accompanying notes are an integral part of the financial statements.
## STATEMENT OF CHANGES IN NET ASSETS

YEAR ENDED DECEMBER 31, 2015

<table>
<thead>
<tr>
<th></th>
<th>Unrestricted Net Assets</th>
<th>Temporarily Restricted Net Assets</th>
<th>Permanently Restricted Net Assets</th>
<th>Total Net Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance at January 1, 2015</td>
<td>$11,920,796</td>
<td>$1,742,984</td>
<td>$642,702</td>
<td>$14,306,482</td>
</tr>
<tr>
<td><strong>Unrestricted Net Assets:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total unrestricted support, including net assets released from restrictions</td>
<td>16,415,414</td>
<td>—</td>
<td>—</td>
<td>16,415,414</td>
</tr>
<tr>
<td>Expenses</td>
<td></td>
<td>17,812,987</td>
<td>—</td>
<td>17,812,987</td>
</tr>
<tr>
<td><strong>(Decrease) in Unrestricted Net Assets</strong></td>
<td>(1,397,573)</td>
<td>—</td>
<td>—</td>
<td>(1,397,573)</td>
</tr>
<tr>
<td><strong>Temporarily Restricted Net Assets:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contributions</td>
<td>—</td>
<td>63,489</td>
<td>—</td>
<td>63,489</td>
</tr>
<tr>
<td>Investment income</td>
<td>—</td>
<td>19,923</td>
<td>—</td>
<td>19,923</td>
</tr>
<tr>
<td>Net assets released from restrictions</td>
<td>—</td>
<td>(70,932)</td>
<td>—</td>
<td>(70,932)</td>
</tr>
<tr>
<td>Realized and unrealized (losses) on investments</td>
<td>—</td>
<td>(10,268)</td>
<td>—</td>
<td>(10,268)</td>
</tr>
<tr>
<td><strong>Increase in Temporarily Restricted Net Assets</strong></td>
<td>—</td>
<td>2,212</td>
<td>—</td>
<td>2,212</td>
</tr>
<tr>
<td><strong>Permanently Restricted Net Assets:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment income</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Increase in Permanently Restricted Net Assets</strong></td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Changes in Net Assets</strong></td>
<td>(1,397,573)</td>
<td>2,212</td>
<td>1</td>
<td>(1,395,360)</td>
</tr>
<tr>
<td><strong>Balance at December 31, 2015</strong></td>
<td>$10,523,223</td>
<td>$1,745,196</td>
<td>$642,703</td>
<td>$12,911,122</td>
</tr>
</tbody>
</table>

*The accompanying notes are an integral part of the financial statements.*
Cash Flows from Operating Activities:

(Decrease) in net assets $ (1,395,360)

Adjustments to reconcile change in net assets to net cash provided by operating activities:

Depreciation 271,073
Unrealized and realized losses on investments 208,896
Unrealized gain on interest rate swap agreement (16,507)

(Increase) decrease in:

Accounts receivable (8,502)
Prepaid expenses and other current assets 184,665
Inventory (12,972)

(Decrease) increase in:

Accounts payable and accrued expenses (97,260)
Deferred income (298,891)

Net Cash (Used in) Operating Activities (1,164,858)

Cash Flows from Investing Activities:

Acquisition of property and equipment (420,952)
Proceeds from sale of investments 841,575
Purchase of investments (851,461)

Net Cash (Used in) Investing Activities (430,838)

Cash Flow from Financing Activities:

Charitable gift annuity liability (7,825)
Proceeds from bank line of credit 500,000
Payments on long-term debt (183,334)

Net Cash Provided by Financing Activities 308,841

Net (Decrease) in Cash (1,286,855)

Cash at beginning of year 2,367,638

Cash at End of Year $ 1,080,783

Supplemental Disclosure for Cash Flows Information

Cash Paid During the Year for:

Interest $ 176,734
Income taxes

$ --

The accompanying notes are an integral part of the financial statements.
Note 1. Summary of Significant Accounting Policies:

Nature of activities: American Meteorological Society was formed in 1919. Interdisciplinary in scope, the Society actively promotes the development and dissemination of information on the atmospheric and related oceanic and hydrologic sciences.

Basis of accounting: The financial statements of American Meteorological Society have been prepared on the accrual basis of accounting in accordance with accounting principles generally accepted in the United States of America (U.S. GAAP) and, accordingly, reflect all significant receivables, payables and other liabilities.

Basis of presentation: Under U.S. GAAP, the Society is required to report information regarding its financial position and activities according to three classes of net assets: unrestricted net assets, temporarily restricted net assets, and permanently restricted net assets.

Net asset categories are described as follows:

Unrestricted net assets include net assets that are not subject to donor-imposed stipulations.

Temporarily restricted net assets include net assets subject to donor-imposed stipulations that may or will be met by actions of the Society and/or the passage of time.

Permanently restricted net assets include contributions which require, by donor restrictions, that the principal be invested in perpetuity and only the income be made available for operations.

Deferred revenue: Revenues from membership dues and subscription fees are recognized over the periods to which the dues and fees relate. Revenues from page charges are recognized in the periods in which the page charges are earned.

Note 1. Summary of Significant Accounting Policies (Continued):

Concentrations of credit risk: Financial instruments that potentially subject the Society to concentrations of credit risk consist primarily of cash (see Note 2) and temporary cash investments. By their nature, all such financial instruments involve risk, including the credit risk of nonperformance by counter parties and the maximum potential loss may exceed the amount recognized in the statement of financial position. At December 31, 2015, in management’s opinion, there was no significant risk of loss from nonperformance of the counter parties to these financial instruments.

Donated services: No amounts have been reflected in the financial statements for donated services. The Society generally pays for services requiring specific expertise. However, many individuals volunteer their time and perform a variety of tasks that assist the Society with various programs and committee assignments.

Expense allocation: Expenses are charged to program and supporting services on the basis of periodic time and expense studies. Administrative and general expenses include those expenses that are not directly identifiable with any other specific function but provide for the overall support and direction of the Society.

Income tax status: The Society is exempt from federal income tax under Section 501(c)(3) of the Internal Revenue Code. However, income from certain activities not directly related to the Society’s tax-exempt purpose is subject to taxation as unrelated business income.

In determining the recognition of uncertain tax positions, the Society applies a more-likely-than-not recognition threshold and determines the measurement of uncertain tax positions considering the amounts and probabilities of the outcomes that could be realized upon ultimate settlement with taxing authorities. As of December 31, 2015, the Society has no uncertain tax positions that qualify for either recognition or disclosure in the financial statements. The Society is not currently under examination by any taxing jurisdiction. The Society’s federal and state tax returns are generally open for examination for three years following the date filed.
Note 1. Summary of Significant Accounting Policies

(Continued):

Inventory: Inventory, consisting of periodicals and books, is stated at the lower of cost, using the first-in, first-out method, or market.

Investments: The Society carries investments in marketable securities with readily determinable fair values and all investments in debt securities at their fair values in the Statement of Financial Position. Unrealized gains and losses are reflected in the accompanying Statement of Activities.

Promises to give: Unconditional promises to give are recognized as revenues in the period received. Unconditional promises to give that are expected to be collected within one year are recorded at net realizable value. Unconditional promises to give that are expected to be collected in future years are recorded at the present value of their future cash flows. The discounts on those amounts are computed using risk-adjusted interest rates applicable to the years in which the promises are received. Amortization of the discounts is included in contribution revenue. Conditional promises to give are recognized when the conditions on which they depend are substantially met. Uncollectible promises to give are expected to be insignificant and an allowance for uncollectible promises to give is not considered necessary.

There were no unconditional promises to give owed to the Society at December 31, 2015.

Property and equipment: Property and equipment are carried at cost or, if donated, at the approximate fair value at the date of donation. Depreciation is computed using primarily the straight-line method over the estimated useful lives of the assets which range from five to thirty-nine years. Additions and betterments of $2,000 or more are capitalized, while maintenance and repairs that do not improve or extend the useful lives of the respective assets are expensed currently.

The Society’s land and buildings are located in a historical district and its original building is classified as a historical structure. The original property is considered to be a historical treasure that is worth preserving perpetually. The Society has the capacity to protect and preserve essentially the service potential of the land and building, and is doing so.

Note 1. Summary of Significant Accounting Policies

(Continued):

Restricted and unrestricted revenue and support: Contributions received are recorded as unrestricted, temporarily restricted or permanently restricted support, depending on the existence or nature of any donor restrictions.

Contributions that are restricted by the donor are reported as an increase in unrestricted net assets if the restriction expires in the reporting period in which the revenue is recognized. All other donor-restricted contributions are reported as an increase in temporarily or permanently restricted net assets, depending on the nature of the restrictions. When a restriction expires, temporarily restricted net assets are released to unrestricted net assets.

Use of estimates: The preparation of financial statements in conformity with U.S. GAAP requires management to make estimates and assumptions that affect the reported amounts of assets and liabilities and disclosure of contingent assets and liabilities at the date of the financial statements and the reported amounts of revenues and expenses during the reporting period. Actual results could differ from those estimates.

Derivative financial instruments: The Society makes use of derivative financial instruments for the purpose of managing interest rate risk. Derivative financial instruments are recorded at fair value.

Fair Values of Financial Instruments: U.S. GAAP defines fair value as the price that would be received to sell an asset or paid to transfer a liability in an orderly transaction between market participants at the measurement date. U.S. GAAP also establishes a framework for the measurement of fair value, and enhances disclosures about fair value measurements.

Interest rate swap agreements are valued at the net present value of future cash flows attributable to the difference between the contractual variable and fixed rates in those agreements adjusted for nonperformance risk of both the counterparty and the Society. The carrying value of all other financial instruments approximates fair value.
Note 1. Summary of Significant Accounting Policies (Continued):

Advertising: The Society uses advertising to promote its programs, bulletins, journals, books and education materials among the audiences it serves. The production costs of advertising are expensed as incurred.

Date of Management’s Review: The Society has evaluated subsequent events through August 1, 2016 which is the date the financial statements were available to be issued.

Note 2. Cash:

The Society places its cash in institutions which are insured by the Federal Deposit Insurance Corporation (FDIC). At times during the year, the bank balances may be in excess of the FDIC insurance limit of $250,000 per institution. At December 31, 2015, the Society’s bank balances exceeded the FDIC limit by approximately $484,900.

Note 3. Investments:

The Society’s investments at December 31, 2015, which are held and managed by outside custodians, consist of stocks, mutual funds and invested cash, including money market funds.

Note 3. Investments (Continued):

U.S. GAAP establishes a fair value hierarchy that prioritizes inputs to valuation techniques used to measure fair value. The three levels of the fair value hierarchy are as follows:

- **Level 1 inputs** are quoted prices (unadjusted) for identical investments in active markets.

- **Level 2 inputs** are quoted prices for similar instruments in active markets; quoted prices for identical or similar instruments in markets that are not active; and model-derived valuations in which all significant inputs and significant value drivers are observable in active markets.

- **Level 3 inputs** are model derived valuations in which one or more significant inputs or significant value drivers are unobservable.

In certain cases, the inputs to measure fair value may result in an asset or liability falling into more than one level of the fair value hierarchy. In such cases, the determination of the classification of an asset or liability within the fair value hierarchy is based on the least determinate input that is significant to the fair value measurement. The Select Investment Program’s assessment of the significance of a particular input to the fair value measurement in its entirety requires judgment and considers factors specific to the asset or liability.

The following table summarizes the Society’s financial assets measured at fair value on a recurring basis in accordance with U.S. GAAP as of December 31, 2015:

<table>
<thead>
<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. corporate stock and mutual funds</td>
<td>$6,725,093</td>
<td>$ —</td>
<td>$ —</td>
</tr>
<tr>
<td>Certificates of deposit</td>
<td>1,069,264</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Money market funds</td>
<td>487,274</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Planned giving assets</td>
<td>464,604</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$8,746,235</td>
<td>$ —</td>
<td>$ —</td>
</tr>
</tbody>
</table>
NOTES TO FINANCIAL STATEMENTS (CONTINUED) YEAR ENDED DECEMBER 31, 2015

Note 3. Investments (Continued):

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>Unrealized Gains</th>
<th>Fair Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invested cash</td>
<td>$487,274</td>
<td>$ —</td>
<td>$487,274</td>
</tr>
<tr>
<td>Mutual funds</td>
<td>4,862,803</td>
<td>1,844,090</td>
<td>6,706,893</td>
</tr>
<tr>
<td>Stocks</td>
<td>1</td>
<td>18,199</td>
<td>18,200</td>
</tr>
<tr>
<td>Gift annuities</td>
<td>487,742</td>
<td>(23,138)</td>
<td>464,604</td>
</tr>
<tr>
<td>Certificates of deposit</td>
<td>1,069,264</td>
<td>$ —</td>
<td>1,069,264</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$6,907,084</td>
<td>$1,839,151</td>
<td>$8,746,235</td>
</tr>
</tbody>
</table>

Included in the accompanying statement of financial position as follows:

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>Unrealized Gains</th>
<th>Fair Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term investments</td>
<td>$6,352,503</td>
<td>$1,844,090</td>
<td>$8,196,593</td>
</tr>
<tr>
<td>Long-term investments</td>
<td>554,581</td>
<td>(4,939)</td>
<td>549,642</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$6,907,084</td>
<td>$1,839,151</td>
<td>$8,746,235</td>
</tr>
</tbody>
</table>

The following schedule summarizes the investment returns and their classification in the statement of activities for the year ended December 31, 2015:

<table>
<thead>
<tr>
<th></th>
<th>Permanently Restricted</th>
<th>Temporarily Restricted</th>
<th>Unrestricted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment income</td>
<td>$1</td>
<td>$19,923</td>
<td>$152,157</td>
</tr>
<tr>
<td>Realized gains on investments</td>
<td>—</td>
<td>24,174</td>
<td>95,067</td>
</tr>
<tr>
<td>Unrealized gains (losses) on</td>
<td>—</td>
<td>(34,442)</td>
<td>(293,695)</td>
</tr>
<tr>
<td>investments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$1</td>
<td>$9,655</td>
<td>$(46,471)</td>
</tr>
</tbody>
</table>

Note 4. Property and Equipment:

Property and equipment consists of the following:

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>$3,651,675</td>
</tr>
<tr>
<td>Building and improvements</td>
<td>8,769,745</td>
</tr>
<tr>
<td>Office equipment and furniture</td>
<td>2,179,425</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>14,600,845</td>
</tr>
<tr>
<td>Less accumulated depreciation</td>
<td>3,113,571</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$11,487,274</td>
</tr>
</tbody>
</table>
Note 5. Line of Credit:

The Society entered into a revolving line of credit agreement with Webster Bank National Association (the “Bank”) in the amount of $500,000. As of December 31, 2015, there was $500,000 outstanding on the line of credit. The line of credit agreement contains financial and other covenants including a maximum leverage provision. At December 31, 2015, the Society was not in compliance with these covenants. However, the Society received a waiver from the bank of these covenants for the year ended December 31, 2015. The line of credit is secured and cross collateralized with the tax exempt bond financing and by a first security interest in all assets of the Society.

Note 6. Long-Term Debt:

The Society entered into a loan agreement with the Massachusetts Development Finance Agency, (the “Issuer”), a public instrumentality of the Commonwealth of Massachusetts in November 2010. The note was issued with bonds, by and among the Issuer, the Society, Webster Massachusetts Security Corporation, (the “Bondholder”), and Webster Bank National Association (the “Paying Agent”). The note is payable in monthly installments of $15,278 plus interest through November 2040. The interest rate on the note is set by the Paying Agent and will be reset from time to time. At December 31, 2015, the interest rate was 3.7075%. The bond is secured by the land and building located at 44 Beacon Street, Boston, Massachusetts with a net book value of $7,169,634 at December 31, 2015.

The note is subject to the same covenants, security and cross collateralization as the line of credit (See Note 5).

Note 6. Long-Term Debt (Continued):

Maturities of long-term debt at December 31, 2015 consist of the following:

<table>
<thead>
<tr>
<th>Year Ending December 31</th>
<th>$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>183,333</td>
</tr>
<tr>
<td>2017</td>
<td>183,333</td>
</tr>
<tr>
<td>2018</td>
<td>183,333</td>
</tr>
<tr>
<td>2019</td>
<td>183,333</td>
</tr>
<tr>
<td>2020</td>
<td>183,333</td>
</tr>
<tr>
<td>Thereafter</td>
<td>3,651,390</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4,568,055</strong></td>
</tr>
</tbody>
</table>

Note 7. Split Interest Agreements:

The Society administers various charitable gift annuities. A charitable gift annuity provides for the payment of distributions to the grantor or other designated beneficiaries over the trust term (usually the designated beneficiary’s lifetime). The portion of the gift annuity attributable to the present value of the future benefits to be received by the Society is recorded in the Statement of Activities as an unrestricted contribution in the period the gift annuity is established. Assets held in the various charitable gift annuities totaled approximately $464,600 at December 31, 2015 and are recorded at fair value in the Society’s Statement of Financial Position.

On an annual basis, the Society revalues the liability to make distributions to the designated beneficiaries based on actuarial assumptions. The present value of the estimated future payments (approximately $152,600 at December 31, 2015) is calculated using a discount rate of 4.5% and applicable mortality tables.
Note 8. Interest Rate Swap Agreement:

U.S. GAAP requires certain derivative financial instruments to be recorded at fair value. An interest rate swap agreement is used by the Society to mitigate the risk of changes in interest rates associated with variable interest rate indebtedness. Under such arrangement, a portion of variable rate indebtedness is converted to fixed rates based on a notional principal amount.

The interest rate swap agreement is a derivative instrument that is required to be marked to market and recorded at fair value on the statement of financial position. At December 31, 2015, the aggregate notional principal amount under the interest rate swap agreement, with a maturity of November 1, 2040, totaled $4,568,055. At December 31, 2015, the estimated fair value of the interest rate swap agreement was a liability of $224,195, and is classified on the statement of financial position as an interest rate swap agreement liability as of December 31, 2015.

As described in Note 3, U.S. GAAP establishes a fair value hierarchy that prioritizes inputs to valuation techniques used to measure fair value.

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interest rate swap</td>
<td>$ —</td>
<td>$224,195</td>
</tr>
</tbody>
</table>

The change in fair value on this interest rate swap agreement was a gain of $16,507 for the year ended December 31, 2015, which is reflected as an unrealized gain on interest rate swap agreement in the accompanying statement of activities.

Note 9. Compensated Absences:

It is the Society’s policy to reasonably estimate each year the amount of accrued vacation compensation that it anticipates to pay in the future. As of December 31, 2015, the Society has an accrued liability of approximately $526,000 related to this policy, which is reflected in the statement of financial position.

Note 10. Program and Supporting Services:

The following program and supporting services are included in the accompanying financial statements:

Membership and Communication
Includes all primary member services, including, among others, the maintenance of the membership database, the certification programs and the publication of the Bulletin.

Journals

Meetings and Exhibits
Includes presenting various meetings throughout the year including the annual meeting and the related exhibits. It also includes short courses offered at the various meetings.

Books and Educational Materials
Includes the production and sale of books published by the Society, distribution throughout North America of WMO publications and sale of educational material for pre-college teachers.

Education and Policy Programs
Includes federal funding and Society support of nationally recognized programs using the study of the atmosphere and ocean to enhance or create an interest in pre-college students in science and engineering. Programs include, among others, AMS/NOAA Cooperative Program for Earth System Education, AMS Summer Policy Colloquium 2015-2018, AMS Climate Studies and Research Opportunities in Space and Earth Sciences. Policy programs work 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.
Note 10. Program and Supporting Services (Continued):

Administrative and General

Includes the functions necessary to maintain a portion of an equitable employment program; ensure an adequate working environment; provide coordination and articulation of the Society’s program strategy through the Office of the Executive Director; secure proper administrative functioning of the Council; maintain competent legal services for the program administration of the Society; and manage the financial and budgetary responsibilities of the Society.

Note 11. Retirement Plan:

The Society has a contributory retirement plan covering substantially all full-time employees. This is a tax deferred annuity plan under Section 403(b) of the U.S. Internal Revenue Code. The plan allows eligible employees to contribute 5% of their compensation through a salary reduction agreement.

The Society contributes 10% of compensation for participating employees. The expense for this plan amounted to $526,386 for the year ended December 31, 2015.

Note 12. Commitments:

The Society leases office space and equipment under various operating leases through March 2027. Under the terms of the office space lease, the Society is obligated to pay escalation rental for certain operating expenses and real estate taxes. Rental expense under the leases amounted to $561,000 for the year ended December 31, 2015 (including charges for operating expenses and taxes). The following is a schedule of future minimum rentals under the leases at December 31, 2015:

<table>
<thead>
<tr>
<th>Year Ending December 31:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>558,957</td>
</tr>
<tr>
<td>2017</td>
<td>571,241</td>
</tr>
<tr>
<td>2018</td>
<td>583,833</td>
</tr>
<tr>
<td>2019</td>
<td>596,739</td>
</tr>
<tr>
<td>2020</td>
<td>545,693</td>
</tr>
<tr>
<td>Thereafter</td>
<td>3,709,499</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$ 6,565,962</strong></td>
</tr>
</tbody>
</table>

Note 13. Endowment Funds:

In accordance with the Uniform Prudent Management of Institutional Funds Act (UPMIFA), the Society is required to act prudently when making decisions to spend or accumulate donor restricted endowment assets and in doing so to consider a number of factors including the duration and preservation of its donor restricted endowment funds. The Society classifies as permanently restricted net assets the original value of gifts donated to the permanent endowment. The remaining portion of the endowment fund that is not classified in permanently restricted net assets is classified as temporarily restricted net assets until those amounts are appropriated for expenditure by the Society in a manner consistent with the standard of prudence prescribed by UPMIFA.

The Society’s endowment consists of approximately 65 individual funds established for a variety of purposes. Its endowment includes both donor-restricted endowment funds and funds designated by the Executive Committee to function as endowments. As required by generally accepted accounting principles, net assets associated with endowment funds including funds designated by the Executive Committee to function as endowments, are classified and reported based on the existence or absence of donor-imposed restrictions. When the donor’s interest is not expressed in relation to the endowment fund, it is the policy of the Organization to record the income, interest, and dividends and accumulated appreciation/depreciation in each endowment fund and appropriate expenditures from each fund in a prudent manner for the uses, benefits, purpose, and duration for which the endowment fund was established. As a result, the income earned each year for each endowment fund is reflected as either unrestricted, temporarily restricted or permanently restricted depending on the intent of the donor when the original gift was made.
Note 13. Endowment Funds (Continued):

Interpretation of Relevant Law: The Executive Committee of the Society has interpreted the Uniform Prudent Management of Institutional Funds Act (UPMIFA) as requiring the preservation of the fair value of the original gift as of the gift date on the donor-restricted endowment funds absent explicit donor stipulations to the contrary. As a result, the Society classifies as permanently restricted net assets (a) the original value of gifts donated to the permanent endowment, (b) the original value of subsequent gifts to the permanent endowment, and (c) accumulations to the permanent endowment made in accordance with the direction of the applicable donor gift instrument at the time the accumulation is added to the fund. The remaining portion of the donor-restricted endowment fund is classified as temporarily restricted net assets until those amounts are appropriated for expenditure by the Society in a manner consistent with the standards of prudence prescribed by UPMIFA. In accordance with UPMIFA, the Society considers the following factors in making a determination to appropriate or accumulate donor-restricted endowment funds:

1. The duration and preservation of the various funds.
2. The purposes of the donor-restricted endowment funds.
3. General economic conditions.
4. The possible effect of inflation and deflation.
5. The expected total return from income and the appreciation of investments.
6. Other resources of the Society.
7. The investment policies of the Society.

Return Objectives and Risk Parameters: The Society has adopted investment and spending policies approved by the Executive Committee for endowment assets that attempt to provide a predictable stream of funding to programs supported by its endowment funds while also maintaining the purchasing power of those endowment assets over the long-term.

Endowment assets include those assets of donor-restricted funds that the Society must hold in perpetuity or for a donor-specified period(s) as well as board-designated funds. Under this policy, as approved by the Executive Committee, the endowment assets are invested in a manner that is intended to contribute to the Society’s total return objectives and preserve principal while maintaining a competitive yield as market conditions dictate.

Strategies Employed for Achieving Objectives: To satisfy its long-term rate-of-return objectives, the Society relies on a total return strategy in which investment returns are achieved through both capital appreciation (realized and unrealized) and current yield (interest and dividends). The Society targets a diversified conservative asset allocation including equity and marketable debt securities to achieve its long-term return objectives within prudent risk constraints.

Spending Policy and How the Investment Objectives Relate to Spending Policy: The Society’s policy of appropriating for distributions of its endowment fund for scholarships, fellowships and other distribution of funds of approximately 3% to 5% is determined based on the donor’s intentions and investment returns as well as taking into consideration the long-term expected return on its endowment, the nature and duration of the individual endowment funds, and the possible effects of inflation. Accordingly, over the long-term, the Society expects the current spending policy to allow its endowment to grow at a normal inflationary rate on an annual basis. This is consistent with the Society’s objective to maintain the purchasing power of the endowment assets held in perpetuity or for a specific term as well as to provide additional growth through new gifts and investment return.
Note 13. Endowment Funds (Continued):

Endowment net assets composition by type of fund as of December 31, 2015:

<table>
<thead>
<tr>
<th>Fund Type</th>
<th>Board Designated</th>
<th>Temporarily Restricted</th>
<th>Permanently Restricted</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donor-restricted endowment funds</td>
<td>$</td>
<td>$ 1,638,805</td>
<td>$ 642,703</td>
<td>$ 2,387,899</td>
</tr>
<tr>
<td>Board-designated endowment funds</td>
<td>779,881</td>
<td></td>
<td></td>
<td>779,881</td>
</tr>
<tr>
<td></td>
<td>$ 779,881</td>
<td>$ 1,638,805</td>
<td>$ 642,703</td>
<td>$ 3,167,780</td>
</tr>
</tbody>
</table>

Changes in endowment net assets for year ended December 31, 2015:

<table>
<thead>
<tr>
<th></th>
<th>Board Designated</th>
<th>Temporarily Restricted</th>
<th>Permanently Restricted</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning of year</td>
<td>$ 1,422,902</td>
<td>$ 1,689,996</td>
<td>$ 642,702</td>
<td>$ 3,808,588</td>
</tr>
<tr>
<td>Investment return:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment income</td>
<td>31,439</td>
<td>19,923</td>
<td>1</td>
<td>51,363</td>
</tr>
<tr>
<td>Net appreciation</td>
<td>(16,511)</td>
<td>(10,268)</td>
<td></td>
<td>(26,779)</td>
</tr>
<tr>
<td>Total investment</td>
<td>1,437,830</td>
<td>1,699,651</td>
<td>642,703</td>
<td>3,833,172</td>
</tr>
<tr>
<td>Contributions</td>
<td>534,082</td>
<td>10,086</td>
<td></td>
<td>597,571</td>
</tr>
<tr>
<td>Appropriation</td>
<td>(1,192,031)</td>
<td>(70,932)</td>
<td></td>
<td>(1,262,963)</td>
</tr>
<tr>
<td>End of year</td>
<td>$ 779,881</td>
<td>$ 1,638,805</td>
<td>$ 642,703</td>
<td>$ 3,167,780</td>
</tr>
</tbody>
</table>

Note 14. Restrictions on Net Assets:

Temporarily restricted net assets consists of contributions presently available for use, but expended only for the purposes specified by the donor. At December 31, 2015, temporarily restricted net assets consist of the following:

<table>
<thead>
<tr>
<th>Fund Type</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scholarship awards</td>
<td>$ 1,210,930</td>
</tr>
<tr>
<td>Hydrology research</td>
<td>170,437</td>
</tr>
<tr>
<td>Charitable gift annuities</td>
<td>144,028</td>
</tr>
<tr>
<td>Remote sensing awards</td>
<td>99,407</td>
</tr>
<tr>
<td>Lecture series awards</td>
<td>50,000</td>
</tr>
<tr>
<td>Student travel awards</td>
<td>62,991</td>
</tr>
<tr>
<td>Student paper awards</td>
<td>7,403</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$ 1,745,196</strong></td>
</tr>
</tbody>
</table>

Note 14. Restrictions on Net Assets (Continued):

Permanently restricted net assets consist of endowment fund assets to be held indefinitely.
<table>
<thead>
<tr>
<th>Unrestricted Net Assets:</th>
<th>Balances January 1, 2015</th>
<th>Receipts and Other Additions</th>
<th>Expenditures and Other Deductions</th>
<th>Total</th>
<th>Appreciation (Depreciation) in Fair Market Value</th>
<th>Balances December 31, 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>$ 10,497,894</td>
<td>$ —</td>
<td>$ 477,369</td>
<td>$ 10,020,525</td>
<td>$ (277,183)</td>
<td>$ 9,743,342</td>
</tr>
<tr>
<td>Board designated funds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td>907,622</td>
<td></td>
<td>690,322</td>
<td>217,300</td>
<td>—</td>
<td>217,300</td>
</tr>
<tr>
<td>Rosen Gift Annuity</td>
<td>124,813</td>
<td>22,118</td>
<td>—</td>
<td>146,931</td>
<td>(11,606)</td>
<td>135,325</td>
</tr>
<tr>
<td>Development</td>
<td>94,328</td>
<td>209,237</td>
<td>210,609</td>
<td>92,956</td>
<td>—</td>
<td>92,956</td>
</tr>
<tr>
<td>Saltzman</td>
<td>84,124</td>
<td>1,005</td>
<td>5,145</td>
<td>79,984</td>
<td>(966)</td>
<td>79,018</td>
</tr>
<tr>
<td>Cooper</td>
<td>62,814</td>
<td>533</td>
<td>1,581</td>
<td>61,766</td>
<td>(129)</td>
<td>61,637</td>
</tr>
<tr>
<td>Scholarship</td>
<td>31,250</td>
<td>79,750</td>
<td>62,000</td>
<td>49,000</td>
<td>—</td>
<td>49,000</td>
</tr>
<tr>
<td>75th Endowment</td>
<td>41,472</td>
<td>287</td>
<td>—</td>
<td>41,759</td>
<td>(173)</td>
<td>41,586</td>
</tr>
<tr>
<td>Student Travel Fund</td>
<td>40,456</td>
<td>993</td>
<td>1,798</td>
<td>39,651</td>
<td>(232)</td>
<td>39,419</td>
</tr>
<tr>
<td>Kalnay Gift Annuity</td>
<td>20,755</td>
<td>5,375</td>
<td>3,030</td>
<td>23,100</td>
<td>(2,271)</td>
<td>20,829</td>
</tr>
<tr>
<td>Glahn</td>
<td>15,476</td>
<td></td>
<td>—</td>
<td>15,476</td>
<td>—</td>
<td>15,476</td>
</tr>
<tr>
<td>Witte Gift Annuity</td>
<td>7,987</td>
<td>6,463</td>
<td>1,541</td>
<td>12,909</td>
<td>—</td>
<td>11,773</td>
</tr>
<tr>
<td>Atlas</td>
<td>1,720</td>
<td>2,276</td>
<td>—</td>
<td>3,996</td>
<td>(1,136)</td>
<td>3,996</td>
</tr>
<tr>
<td>Fellowship</td>
<td>(15,685)</td>
<td>324,335</td>
<td>305,170</td>
<td>3,480</td>
<td>—</td>
<td>3,480</td>
</tr>
<tr>
<td>Reeves</td>
<td>1,071</td>
<td>4,532</td>
<td>3,000</td>
<td>2,603</td>
<td>—</td>
<td>2,603</td>
</tr>
<tr>
<td>Roberts</td>
<td>2,154</td>
<td></td>
<td>2,154</td>
<td>2,154</td>
<td>—</td>
<td>2,154</td>
</tr>
<tr>
<td>Ooyama</td>
<td>1,518</td>
<td>527</td>
<td>2,045</td>
<td>2,045</td>
<td>—</td>
<td>2,045</td>
</tr>
<tr>
<td>Friday</td>
<td>684</td>
<td>255</td>
<td>939</td>
<td>939</td>
<td>—</td>
<td>939</td>
</tr>
<tr>
<td>Digiquartz</td>
<td>321</td>
<td>1</td>
<td>322</td>
<td>322</td>
<td>—</td>
<td>322</td>
</tr>
<tr>
<td>Hobbs</td>
<td>22</td>
<td>1</td>
<td>23</td>
<td>23</td>
<td>—</td>
<td>23</td>
</tr>
<tr>
<td><strong>Total Unrestricted Net Assets</strong></td>
<td><strong>$ 11,920,796</strong></td>
<td><strong>$ 657,688</strong></td>
<td><strong>$ 1,761,565</strong></td>
<td><strong>$ 10,816,919</strong></td>
<td><strong>$ (293,696)</strong></td>
<td><strong>$ 10,523,223</strong></td>
</tr>
<tr>
<td>Scholarship awards:</td>
<td>Balance</td>
<td>Receipts</td>
<td>Expenditures</td>
<td>Total</td>
<td>Appreciation (Depreciation) in Fair Market Value</td>
<td>Balance</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------</td>
<td>----------</td>
<td>--------------</td>
<td>-------</td>
<td>-----------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Orville</td>
<td>$392,578</td>
<td>$2,662</td>
<td>$5,000</td>
<td>$390,240</td>
<td>$(1,042)</td>
<td>$389,198</td>
</tr>
<tr>
<td>Hagemeyer Unitrust</td>
<td>147,111</td>
<td>2,492</td>
<td>3,145</td>
<td>146,458</td>
<td>(5,686)</td>
<td>140,772</td>
</tr>
<tr>
<td>NWSA</td>
<td>133,045</td>
<td>263</td>
<td>10,000</td>
<td>123,308</td>
<td></td>
<td>123,308</td>
</tr>
<tr>
<td>Baum</td>
<td>82,975</td>
<td>480</td>
<td>5,000</td>
<td>78,455</td>
<td>(349)</td>
<td>78,106</td>
</tr>
<tr>
<td>Ooyama</td>
<td>70,438</td>
<td>200</td>
<td>2,000</td>
<td>68,638</td>
<td>(292)</td>
<td>68,346</td>
</tr>
<tr>
<td>David Johnson</td>
<td>64,284</td>
<td>797</td>
<td>3,145</td>
<td>61,936</td>
<td>(738)</td>
<td>61,198</td>
</tr>
<tr>
<td>Houghton</td>
<td>58,265</td>
<td>620</td>
<td>—</td>
<td>58,885</td>
<td>(199)</td>
<td>58,686</td>
</tr>
<tr>
<td>L. Johnson</td>
<td>56,240</td>
<td>2,433</td>
<td>—</td>
<td>56,673</td>
<td>(173)</td>
<td>56,500</td>
</tr>
<tr>
<td>Vonnegut–Schaefer</td>
<td>57,874</td>
<td>1,044</td>
<td>5,145</td>
<td>53,773</td>
<td>(930)</td>
<td>52,843</td>
</tr>
<tr>
<td>Roberts</td>
<td>49,440</td>
<td>6</td>
<td>2,000</td>
<td>47,446</td>
<td>—</td>
<td>47,446</td>
</tr>
<tr>
<td>Glahn</td>
<td>47,946</td>
<td>1,668</td>
<td>2,500</td>
<td>47,114</td>
<td>(370)</td>
<td>46,744</td>
</tr>
<tr>
<td>Friday</td>
<td>36,117</td>
<td>—</td>
<td>2,500</td>
<td>33,617</td>
<td>(173)</td>
<td>33,444</td>
</tr>
<tr>
<td>Grau</td>
<td>34,861</td>
<td>6</td>
<td>5,000</td>
<td>29,867</td>
<td>—</td>
<td>29,867</td>
</tr>
<tr>
<td>Reed</td>
<td>18,442</td>
<td>97</td>
<td>—</td>
<td>18,539</td>
<td>—</td>
<td>18,539</td>
</tr>
<tr>
<td>Merewether</td>
<td>7,648</td>
<td>1</td>
<td>—</td>
<td>7,649</td>
<td>—</td>
<td>7,649</td>
</tr>
<tr>
<td>Milham</td>
<td>3,239</td>
<td>—</td>
<td>—</td>
<td>3,239</td>
<td>—</td>
<td>3,239</td>
</tr>
<tr>
<td>Hanks Scholarship</td>
<td>2,939</td>
<td>53</td>
<td>—</td>
<td>2,992</td>
<td>—</td>
<td>2,992</td>
</tr>
<tr>
<td>Wark</td>
<td>7,438</td>
<td>3,056</td>
<td>5,145</td>
<td>5,349</td>
<td>(2,953)</td>
<td>2,396</td>
</tr>
<tr>
<td>Namias</td>
<td>2,347</td>
<td>647</td>
<td>145</td>
<td>2,849</td>
<td>(600)</td>
<td>2,249</td>
</tr>
<tr>
<td>Hope</td>
<td>1,710</td>
<td>385</td>
<td>—</td>
<td>2,095</td>
<td>(232)</td>
<td>1,863</td>
</tr>
<tr>
<td>Digiquartz</td>
<td>500</td>
<td>—</td>
<td>—</td>
<td>500</td>
<td>—</td>
<td>500</td>
</tr>
<tr>
<td>Kreitzberg</td>
<td>(792)</td>
<td>227</td>
<td>2,000</td>
<td>(2,565)</td>
<td>—</td>
<td>(2,565)</td>
</tr>
<tr>
<td>Murphy</td>
<td>(2,181)</td>
<td>364</td>
<td>2,000</td>
<td>(3,817)</td>
<td>(232)</td>
<td>(4,049)</td>
</tr>
<tr>
<td>Schroeder</td>
<td>(3,679)</td>
<td>688</td>
<td>5,000</td>
<td>(7,991)</td>
<td>(350)</td>
<td>(8,341)</td>
</tr>
<tr>
<td>Hydrology research:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horton</td>
<td>169,434</td>
<td>1,525</td>
<td>—</td>
<td>170,959</td>
<td>(522)</td>
<td>170,437</td>
</tr>
<tr>
<td>Charitable gift annuities:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gift Annuities</td>
<td>138,181</td>
<td>27,679</td>
<td>3,545</td>
<td>162,315</td>
<td>(18,287)</td>
<td>144,028</td>
</tr>
<tr>
<td>Remote sensing awards:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlas</td>
<td>103,371</td>
<td>2,350</td>
<td>5,000</td>
<td>100,721</td>
<td>(1,314)</td>
<td>99,407</td>
</tr>
<tr>
<td>Lecture series awards:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Gajdecki</td>
<td>—</td>
<td>50,000</td>
<td>—</td>
<td>50,000</td>
<td>—</td>
<td>50,000</td>
</tr>
<tr>
<td>Student travel awards:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wesley</td>
<td>34,859</td>
<td>1,588</td>
<td>408</td>
<td>36,039</td>
<td>—</td>
<td>36,039</td>
</tr>
<tr>
<td>K. Spengler</td>
<td>8,209</td>
<td>3,949</td>
<td>—</td>
<td>12,158</td>
<td>—</td>
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Total Temporarily Restricted Net Assets: $1,742,984 $107,586 $70,932 $1,779,638 $(34,442) $1,745,196
## SCHEDULE OF NET ASSETS
### BY RESTRICTION (CONTINUED)
#### YEAR ENDED DECEMBER 31, 2015

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<th>Expenditures and Other Deductions</th>
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<td>$</td>
<td>$</td>
<td>$ 642,703</td>
<td>$</td>
<td>$ 642,703</td>
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Eyewitness: Evolution of the Atmospheric Sciences describes how the atmospheric sciences were transformed in the span of the author’s professional career from its origins in primitive weather forecasting to its current focus on numerical modeling of environmental change. It describes the author’s observations of persons, events, and institutions beginning with graduate study during the Second World War and moving on to continuing expansion of the atmospheric sciences and technologies, through development of a major university department, development of new scientific and professional institutions, and to the role that the science of the atmosphere now plays in climate change and other issues of social and political policy.

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ABOUT THE AUTHOR
Robert G. Fleagle earned degrees in physics and meteorology at The Johns Hopkins University and New York University and began his professional career in 1948 at the University of Washington (UW). His research has focused on the structure of midlatitude cyclones, the physics and structure of the surface boundary layer, and processes of air–sea interaction. He is the author of about 100 papers published in scientific journals and of books on atmospheric physics and global environmental change. Applications of science to social and political policy have been important motivations for his career and have occupied his attention increasingly as the decades passed.

Fleagle participated at close range in the beginnings and growth of a major university department and of the University Corporation for Atmospheric Research (UCAR). In 1963 and 1964 he served as a staff specialist in the Office of Science and Technology, Executive Office of the President, and in 1977–78 he served as consultant to the National Oceanic and Atmospheric Administration. He has held many administrative posts including chairman of the UW Department of Atmospheric Sciences (1967–77), chairman of the National Academy of Sciences Committee on Atmospheric Sciences (1969–73),
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