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“Big Data Assimilation” Revolutionizing Severe Weather Prediction

T. Miyoshi et al.

Visualizing Vapor Pressure
A Mechanical Demonstration of Liquid–Vapor Phase Equilibrium

D. Lamb and R. A. Shaw

Statistical Characteristic of Heavy Rainfall Associated with Typhoons near Taiwan Based on High-Density Automatic Rain Gauge Data

C.-C. Wu et al.

Improving the Mapping and Prediction of Offshore Wind Resources (IMPOWR) Experimental Overview and First Results

B. A. Colle et al.

Satellite and In Situ Salinity Understanding Near-Surface Stratification and Subfootprint Variability

J. Boutin et al.

Analysis of an Observing System Experiment for the Joint Polar Satellite System

S. Lord et al.

Bridging Research to Operations Transitions Status and Plans of Community GSI

H. Shao et al.

The North American Soil Moisture Database Development and Applications

S. M. Quiring et al.

Worldwide Survey of Awareness and Needs Concerning Reanalyses and Respondents Views on Climate Services

H. Gregow et al.

Feeling the Pulse of the Stratosphere An Emerging Opportunity for Predicting Continental-Scale Cold-Air Outbreaks 1 Month in Advance

M. Cai et al.

Supplements are available online at http://journals.ametsoc.org/toc/bams/97/8
NOWCAST

1333 NEWS AND NOTES
Ocean Wave Interactions Uncovered…Ocean Mechanism Cuts Down Hurricane Strength Near Landfall…Connecting Irrigation to Climate on a Continental Scale

1339 ON THE WEB

1339 CONFERENCE NOTEBOOK

1341 INFORMATION MANAGEMENT
Impacts of Climate Extremes in Brazil: The Development of a Web Platform for Understanding Long-Term Sustainability of Ecosystems and Human Health in Amazonia (PULSE-Brazil)

DEPARTMENTS

1517 CALENDAR OF MEETINGS

1522 CALL FOR PAPERS

1526 NOMINATION SUBMISSIONS

1529 CORPORATION AND INSTITUTIONAL MEMBERS

1533 CLASSIFIEDS

1535 INDEX TO ADVERTISERS

1536 PUBLICATION ORDER FORM

The Bulletin of the American Meteorological Society is the official organ of the Society, devoted to editorials, articles of interest to a large segment of the membership, professional and membership news, announcements, and Society activities. Editing and publishing are under the direction of Keith L. Seitter, executive director. Contributors are encouraged to send proposals to be considered for publication. For guidance on preparation and style, see the Authors’ Resource Center online at www.ametsoc.org/pubs/arcindex.html.


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Few aphorisms have seeped into our lives more pervasively than “Measure what you treasure.” For better or worse, it is a sign of society trying very hard to emulate science. This obsession with data collection now pervades all walks of life. Dieters weigh every ounce of food they eat. School administrators fire teachers based on their students’ test scores. Businesses sell off whole divisions to the tune of the latest balance sheets.

Thanks to a somewhat misapplied admiration of science, the spreadsheet has become the ultimate justification. It was not always so. My grandfather, for example, sifted through piles of sales reports and expense sheets in his business. But he also prowled every inch of his warehouse and sales spaces, using experience and intuition to uncover the minutiae that made the bottom line. He treasured customer relationships above all, but he never needed to quantify them: either people came back for more, or they didn’t.

Indeed, the things that really matter are hard to measure. In life, the treasure of personal relationships and dreams elude measurement. Science, however, is not life. In science, quantification is everything. Our next Annual Meeting is themed, “Observations Lead the Way,” and perhaps it is no coincidence that it takes place in Seattle, the city that not only supplies us with popular spreadsheet software but also brought the Gross National Happiness Index into modern American policymaking.

Our Seattle meeting will underscore the scientific community’s reliance on data. This issue of BAMS, too, offers plenty of examples of articles that are primarily about documenting and measuring things: whether it’s soil moisture, coastal wind power potential, or ocean salinity. In society, however, data don’t just drive inquiry. The modern-day adaptation of scientific management to personal happiness and to public policy means that data affect lives. Increasingly, in AMS meetings and BAMS—and most obviously in the State of the Climate mailed with this issue—we see the same ethos. Atmospheric and other environmental data not only drive science but also drive decisions.

When data are the touchstone of success and failure, sustainability and happiness, it becomes increasingly important to emulate science at its best. Scientists may seem to measure everything, but they know they can’t. They measure with forethought. The State of the Climate is continuously evolving to reflect what we know and need to know. This year’s edition, for example, is the first to track midtropospheric temperature anomalies. Meanwhile, Chun-Chieh Wu and colleagues show how the unevenly distributed observing system in Taiwan must be improved to capture important peaks and variations in rainfall from typhoons (p. 1363).

We can all agree that we treasure our world. To create a true culture of evidence, we must pay attention to both what we measure and how we measure it. That is the ultimate homage to science.

—Jeff Rosenfeld, Editor-in-Chief

“BIG DATA ASSIMILATION” REVOLUTIONIZING SEVERE WEATHER PREDICTION

Sudden local severe weather is a threat, and we explore what the highest-end supercomputing and sensing technologies can do to address this challenge. Here we show that using the Japanese flagship “K” supercomputer, we can synergistically integrate “big simulations” of 100 parallel simulations of a convective weather system at 100-m grid spacing and “big data” from the next-generation phased array weather radar that produces a high-resolution 3-dimensional rain distribution every 30 s—two orders of magnitude more data than the currently used parabolic-antenna radar. This “big data assimilation” system refreshes 30-min forecasts every 30 s, 120 times more rapidly than the typical hourly updated systems operated at the world’s weather prediction centers. A real high-impact weather case study shows encouraging results of the 30-s-update big data assimilation system. (Page 1347)

VISUALIZING VAPOR PRESSURE: A MECHANICAL DEMONSTRATION OF LIQUID–VAPOR PHASE EQUILIBRIUM

Water phase transitions are central to climate and weather. Yet it is a common experience that the principles of phase equilibrium are challenging to understand and teach. A simple mechanical analogy has been developed to demonstrate key principles of liquid evaporation and the temperature dependence of equilibrium vapor pressure. The system is composed of a circular plate with a central depression and several hundred metal balls. Mechanical agitation
of the plate causes the balls to bounce and interact in much the same statistical way that molecules do in real liquid–vapor systems. The data, consisting of the number of balls escaping the central well at different forcing energies, exhibit a logarithmic dependence on the reciprocal of the applied energy (analogous to thermal energy $k_n^2T$) that is similar to that given by Boltzmann statistics and the Clausius–Clapeyron equation. These results demonstrate that the enthalpy (i.e., latent heat) of evaporation is well interpreted as the potential energy difference between molecules in the vapor and liquid phases, and it is the fundamental driver of vapor pressure increase with temperature. Consideration of the uncertainties in the measurements shows that the mechanical system is described well by Poisson statistics. The system is simple enough that it can be duplicated for qualitative use in atmospheric science teaching, and an interactive animation based on the mechanical system is available online for instructional use (http://phy.mtu.edu/vpt/). (Page 1355)

**STATISTICAL CHARACTERISTIC OF HEAVY RAINFALL ASSOCIATED WITH TYPHOONS NEAR TAIWAN BASED ON HIGH-DENSITY AUTOMATIC RAIN GAUGE DATA**

This study utilizes data compiled over 21 years (1993–2013) from the Central Weather Bureau of Taiwan to investigate the statistical characteristics of typhoon-induced rainfall for 53 typhoons that have impacted Taiwan. In this work the data are grouped into two datasets: one includes 21 selected conventional weather stations (referred to as Con-ST), and the other contains all the available rain gauges (250–500 gauges, mostly automatic ones; referred to as All-ST). The primary aim of this study is to understand the potential impacts of the different gauge distributions between All-ST and Con-ST on the statistical characteristics of typhoon-induced rainfall. The analyses indicate that although the average rainfall amount calculated with Con-ST is statistically similar to that with All-ST, the former cannot identify the precipitation extremes and rainfall distribution appropriately, especially in mountainous areas. Because very few conventional stations are located over the mountainous regions, the cumulative frequency obtained solely from Con-ST is not representative. As compared to the results from All-ST, the extreme rainfall assessed from Con-ST is, on average, underestimated by 23%–44% for typhoons approaching different portions of Taiwan. The uneven distribution of Con-ST, with only three stations located in the mountains higher than 1000 m, is likely to cause significant biases in the interpretation of rainfall patterns. This study illustrates the importance of the increase in the number of available stations in assessing the long-term rainfall characteristic of typhoon-associated heavy rainfall in Taiwan. (Page 1363)

**IMPROVING THE MAPPING AND PREDICTION OF OFFSHORE WIND RESOURCES (IMPOWR): EXPERIMENTAL OVERVIEW AND FIRST RESULTS**

The wind resource offshore of the East Coast of the United States is well known for its potential to provide abundant, clean, renewable, and domestic electricity. However, limited observations from this region are recorded at heights above the water that penetrate significantly into the planetary boundary layer (PBL). As a result, mesoscale models have been used to characterize the offshore wind resource in this region but have not been evaluated fully within the PBL due to the scarcity of observations. This paper describes the setup and some early results from the Improving the Mapping and Prediction of Offshore Wind Resources (IMPOWR) field study conducted in the Nantucket Sound area in 2013/14. The IMPOWR campaign provides a rich dataset of observations within the PBL from a variety of sources: high-frequency Long-EZ aircraft, a multilevel atmospheric and oceanic tower in Nantucket Sound, and lidars on the south shore of eastern Long Island and Block Island. In addition to new data for model validation and wind resource assessment, the IMPOWR field campaign provides new insights on meteorological features important for wind power development, such as the New York Bight jet and shallow marine layer. (Page 1377)

**SATELLITE AND IN SITU SALINITY: UNDERSTANDING NEAR-SURFACE STRATIFICATION AND SUBFOOTPRINT VARIABILITY**

Remote sensing of salinity using satellite-mounted microwave radiometers provides new perspectives for studying ocean dynamics and the global hydrological cycle. Calibration and validation of these measurements is challenging because satellite and in situ methods measure salinity differently. Microwave radiometers measure the salinity in the top few centimeters of the ocean,
whereas most in situ observations are reported below a depth of a few meters. Additionally, satellites measure salinity as a spatial average over an area of about 100 × 100 km². In contrast, in situ sensors provide pointwise measurements at the location of the sensor. Thus, the presence of vertical gradients in, and horizontal variability of, sea surface salinity complicates comparison of satellite and in situ measurements. This paper synthesizes present knowledge of the magnitude and the processes that contribute to the formation and evolution of vertical and horizontal variability in near-surface salinity. Rainfall, freshwater plumes, and evaporation can generate vertical gradients of salinity, and in some cases these gradients can be large enough to affect validation of satellite measurements. Similarly, mesoscale to submesoscale processes can lead to horizontal variability that can also affect comparisons of satellite data to in situ data. Comparisons between satellite and in situ salinity measurements must take into account both vertical stratification and horizontal variability. (Page 1391)

**ANALYSIS OF AN OBSERVING SYSTEM EXPERIMENT FOR THE JOINT POLAR SATELLITE SYSTEM**

The Joint Polar Satellite System (JPSS) is a key contributor to the next-generation operational polar-orbiting satellite observing system. In the JPSS era, the complete polar-orbiting observing system will be comprised of two satellites—in the midmorning (mid-AM) and afternoon (PM) orbits—each with thermodynamic sounding capabilities from both microwave and hyperspectral infrared instruments. JPSS will occupy the PM orbit, while the Meteorological Operational (MetOp) system, sponsored by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), will occupy the mid-AM orbit.

While the current polar-orbiting satellite system has been thoroughly evaluated, information about its resilience and efficacy in the JPSS era is needed. A 7-month (August 2012–February 2013) observing system experiment (OSE) was run with the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS). Observations were selected from operational satellite data platforms to be representative of the polar-orbiting data in the JPSS era.

Overall, removing data from the PM orbit produced inferior scores, with the impact greater in the Southern Hemisphere (SH) than in either the Northern Hemisphere (NH) or the tropics.

For the entire 7 months, the time-mean 500-hPa geopotential height anomaly correlation (Z500AC) decreased by 0.005 and 0.013 in the NH and SH, respectively—both of which are statistically significant at the 95% level. Additionally, a detailed statistical analysis of the distribution of Z500AC skill scores is presented and compared with historical accuracy data. It was determined that eliminating PM orbit data resulted in a higher probability of producing low scores and a lower probability of producing high scores, counter to the trend in GFS forecast skill over the last 20 years. (Page 1409)

**BRIDGING RESEARCH TO OPERATIONS TRANSITIONS: STATUS AND PLANS OF COMMUNITY GSI**

With a goal of improving operational numerical weather prediction (NWP), the Developmental Testbed Center (DTC) has been working with operational centers, including, among others, the National Centers for Environmental Prediction (NCEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and the U.S. Air Force, to support numerical models/systems and their research, perform objective testing and evaluation of NWP methods, and facilitate research-to-operations transitions. This article introduces the first attempt of the DTC in the data assimilation area to help achieve this goal. Since 2009, the DTC, NCEP’s Environmental Modeling
Center (EMC), and other developers have made significant progress in transitioning the operational Gridpoint Statistical Interpolation (GSI) data assimilation system into a community-based code management framework. Currently, GSI is provided to the public with user support and is open for contributions from internal developers as well as the broader research community, following the same code transition procedures. This article introduces measures and steps taken during this community GSI effort followed by discussions of encountered challenges and issues. The purpose of this article is to promote contributions from the research community to operational data assimilation capabilities and, furthermore, to seek potential solutions to stimulate such a transition and, eventually, improve the NWP capabilities in the United States. (Page 1427)

THE NORTH AMERICAN SOIL MOISTURE DATABASE: DEVELOPMENT AND APPLICATIONS

Soil moisture is an important variable in the climate system that integrates the combined influence of the atmosphere, land surface, and soil. Soil moisture is frequently used for drought monitoring and climate forecasting. However, in situ soil moisture observations are not systematically archived and there are relatively few national soil moisture networks. The lack of observed soil moisture data makes it difficult to characterize long-term soil moisture variability and trends. The North American Soil Moisture Database (NASMD) is a new high-quality observational soil moisture database. It includes over 1,800 monitoring stations in the United States, Canada, and Mexico, making it the largest collection of in situ soil moisture observations in North America. Data are collected from multiple sources, quality controlled, and integrated into an online database (soilmoisture.tamu.edu). Here we describe the development of the database, including quality control/quality assurance, standardization, and collection of metadata. The utility of the NASMD is demonstrated through an analysis of the inter- and intraannual variability of soil moisture from multiple networks. The NASMD is a useful tool for drought monitoring and forecasting, calibrating/validating satellites and land surface models, and documenting how soil moisture influences the climate system on seasonal to interannual time scales. (Page 1441)

WORLDWIDE SURVEY OF AWARENESS AND NEEDS CONCERNING REANALYSES AND RESPONDENTS VIEWS ON CLIMATE SERVICES

A worldwide online survey about user awareness of reanalyses and climate services was conducted in the period from November 2013 to February 2014 by the Coordinating Earth Observation Data Validation for Re-Analysis for Climate Services (CORE-CLIMAX) project. The 2,578 respondents were mostly users of global reanalyses [particularly the European Centre for Medium-Range Weather Forecasts (ECMWF), National Centers for Environmental Prediction (NCEP), National Aeronautics and Space Administration (NASA), and Japan Meteorological Agency (JMA) reanalyses]. They answered queries arranged in 11 sections by choosing from prepared check-box responses and left several hundred free comments. Here, we analyze responses related to characteristics of reanalysis data and the perceived obstacles for using reanalysis in climate services. After examining responses from all survey participants, we focus on the answers from subgroups working in specific disciplines related to natural resource management: freshwater, agriculture and food production, forestry, and energy. Although the survey attracted mostly self-selected respondents from the education and public research and development (R&D) sectors, one-third of the energy-related subgroup were from the private sector. A large majority (91%) of the respondents use ECMWF reanalyses, but other reanalysis products are also widely used by them. Respondents expressed desire for reanalysis development in the areas of 1) training and online plotting tools, 2) more frequent updates, 3) explanations about uncertainties (the energy subgroup emphasizes this), 4) smaller biases, 5) less restrictive data policy, and 6) higher temporal and spatial resolution (the energy and water subgroups highlight this). Additionally, the subgroups (excluding energy) expressed interest in including in future climate services activities for applied weather and climate research for impact assessment and/or statistical impact analyses for improving weather warnings and their criteria. (Page 1461)

FEELING THE PULSE OF THE STRATOSPHERE: AN EMERGING OPPORTUNITY FOR PREDICTING CONTINENTAL-SCALE COLD-AIR OUTBREAKS 1 MONTH IN ADVANCE

Extreme weather events such as cold-air outbreaks (CAOs) pose
great threats to human life and the socioeconomic well-being of modern society. In the past, our capability to predict their occurrences has been constrained by the 2-week predictability limit for weather. We demonstrate here for the first time that a rapid increase of air mass transported into the polar stratosphere, referred to as the pulse of the stratosphere (PULSE), can often be predicted with a useful degree of skill 4–6 weeks in advance by operational forecast models. We further show that the probability of the occurrence of continental-scale CAOs in midlatitudes increases substantially above normal conditions within a short time period from 1 week before to 1–2 weeks after the peak day of a PULSE event. In particular, we reveal that the three massive CAOs over North America in January and February of 2014 were preceded by three episodes of extreme mass transport into the polar stratosphere with peak intensities reaching a trillion tons per day, twice that on an average winter day. Therefore, our capability to predict the PULSEs with operational forecast models, in conjunction with its linkage to continental-scale CAOs, opens up a new opportunity for 30-day forecasts of continental-scale CAOs, such as those occurring over North America during the 2013/14 winter. A real-time forecast experiment inaugurated in the winter of 2014/15 has given support to the idea that it is feasible to forecast CAOs 1 month in advance. (Page 1475)
New Research Links

Acoustic and Gravity Waves

Scientists have for the first time established a solid relationship between surface gravity waves and acoustic gravity waves. Acoustic waves are extremely quick and long sound waves that sometimes reach hundreds of kilometers in length and propagate through the ocean at the speed of sound, picking up water, nutrients, and other particles as they go. They are generally caused by powerful oceanic events like underwater earthquakes and landslides. Surface gravity waves, or surface ocean waves, travel at a much slower pace on top of the ocean. Usama Kadri and Triantaphyllos Akylas of the Massachusetts Institute of Technology developed a general theory connecting the two types of waves after discovering that two surface gravity waves approaching each other oscillating at comparable frequencies can release almost all of their initial energy as an acoustic wave, which then transports this energy much faster and deeper into the water. While the scientists found this synergy can occur in any part of the ocean, it is more common in areas where surface gravity waves reflect from the edges of continental shelves and interact.

The research, which could have valuable implications for marine life, water transport, CO$_2$ and heat distribution, and tsunami warnings, was published recently in the Journal of Fluid Mechanics.

The discovery was surprising because the properties of gravity waves and acoustic waves differ greatly, in both length and time scales. Surface gravity waves are restored and stabilized mainly by gravity, but gravity has a minimal effect on sound waves. Water’s compressibility allows pressure waves (e.g., sound waves) to pass through it. But compressibility and gravity are not factored in typical water wave equations that characterize ocean wave interactions, and “without compressibility and gravity, we cannot describe low-frequency sound waves correctly,” says Kadri; therefore such equations normally don’t apply to acoustic gravity waves. “This is one of the reasons why researchers have mostly overlooked acoustic gravity waves,” he notes.

Kadri and Akylas derived a new wave equation that includes both compressibility and gravity. Their wave equation also contains higher-order nonlinear terms, because while in linear theory surface gravity waves do not feel each other or exchange energy, Kadri explains, “in reality the picture is more complicated, and nonlinear effects may come into play, resulting in energy exchange and even generation of new waves, sometimes. Here, at specific frequency ranges, gravity waves can actually produce an acoustic wave that has completely different properties—and that is amazing.”

ECHOES

“If something were to go wrong it would be very, very bad.”

—RICHARD BENEVILLE, mayor of Nome, Alaska, on the plan for a luxury cruise ship to sail through the Northwest Passage in the Arctic next summer. The Crystal Serenity cruise ship—which at 820 feet in length and 105 feet wide is larger than the Titanic—is raising concerns with both the U.S. and Canadian coast guards and government officials. With Arctic sea ice at the lowest level ever recorded, shipping traffic has increased along with the necessity of coast guard rescues. Officials say the danger lies in the massive size of the boat and the challenge of rescuing more than 1,000 passengers up to 1,000 miles from the nearest coast guard base if it were to sink (not to mention the lack of roads, unreliable cellphone reception, and sparse medical facilities in the area). For those willing to take on the potential risks, the trip—which leaves from Seward, Alaska, in August 2017 and travels through the Bering Strait and Northwest Passage to New York City over 32 days—comes with a starting price tag of close to $22,000. [SOURCE: weather.com]
With the newly created equation, Kadri analyzed the theoretical interactions of a wave triad with two surface gravity waves and one acoustic gravity wave, and derived evolution equations, which explain how the waves’ amplitudes change during their energy exchange. The equations showed that the two surface waves moving toward each other at a similar frequency and amplitude convert up to 95% of their energy into an acoustic gravity wave as they meet and pass through each other. Depending on the initial amplitudes and frequencies of the surface gravity waves, this energy can fluctuate, but even when the surface gravity waves travel in the form of short bursts, they can still transfer more than 20% of their energy to acoustic gravity waves.

“This is incredible, just to think that these waves are so different,” Kadri says. “Having them sharing energy is really exciting; this explains how some of the energy that comes from the atmosphere, from the sun and the wind, to the upper part of the ocean, can actually be driven to roll in the deep ocean through acoustic gravity waves.”

The study’s findings could be used by scientists to better understand the interactions between surface and deep-ocean waters, as well as the effects of the atmosphere on surface waves. Additionally, Kadri hopes the research will be helpful in creating a technique to identify acoustic gravity waves that precede a tsunami.

“Severe sea states, such as tsunamis, rogue waves, storms, landslides, and even meteorite falls, can all generate acoustic gravity waves,” Kadri notes. “We hope we can use these waves to set an early alarm for severe sea states in general and tsunamis in particular, and potentially save lives.” [SOURCE: Massachusetts Institute of Technology]
reached land. It turns out that the potency of Irene was suppressed by a natural process that curtails the warm near-shore ocean temperatures that feed summertime tropical storms. The finding, published recently in *Nature Communications*, could lead to improved hurricane-intensity forecasting, which still lags behind hurricane-track forecasting improvements.

Researchers initiated the study as Irene stormed up the coast in August of 2011. New Jersey residents and visitors were told to evacuate beaches and other coastal areas, but as noted by the study’s lead author, Scott Glenn of Rutgers University, when the storm arrived, “nothing happened on the beach.” While Irene was still plenty strong—it ranks as the seventh-costliest hurricane in U.S. history—its winds did not reach the levels that were predicted by forecasters. During the storm, the researchers took satellite and radar data, as well as wind and temperature readings from offshore buoys and various data from an autonomous underwater glider. The measurements revealed that Irene’s powerful winds caused warm surface waters just off the coast to mix with the cold bottom layer of the ocean, promptly cooling the surface waters as the eye of the storm approached. These cooler waters diminished the storm’s intensity before it reached land.

“Satellite imagery from before and after the storm revealed that the ocean surface cooled up to 11 degrees Celsius, or 20 degrees Fahrenheit,” notes coauthor Oscar Schofield, also of Rutgers.

The researchers then looked at 10 other summertime Atlantic storms from the years 1985–2015, studying only summer storms because that is when coastal waters of the mid-Atlantic are at their peak temperature. They found that “the cooling occurred in every [studied] hurricane that crossed the mid-Atlantic coastal waters in summer,” says coauthor Robert Forney, a Rutgers undergraduate student. They even found evidence of the same process in the Pacific Ocean in 2011’s Typhoon Muifa, which weakened after crossing the Yellow Sea.

Ocean physics patterns causing cooling—typically upwelling—had previously been observed in deeper ocean waters well offshore, but never in coastal areas, and the researchers believe including coastal water conditions in hurricane intensity forecasts could reduce emergency preparation costs and enhance the public’s trust in forecasts.

Study coauthor Greg Seroka of Rutgers calls the finding “a missing piece required to close the intensity gap” for landfalling summer hurricanes. [Sources: Rutgers University, *Scientific American*]

**STUDY FINDS FAR-REACHING CLIMATE EFFECTS OF ASIAN IRRIGATION**

While most studies of irrigation’s influence on climate have focused on its effects on hydrological and energy cycles, new research published in *Geophysical Research Letters* has discovered that irrigation can have intercontinental impacts.

For the study, researchers utilized the Max Planck Institute for Meteorology’s Earth System Model, and included an irrigation scheme in the land portion of the model. They focused on South Asia, where rice production has given rise to the world’s largest share of irrigation systems. Model results showed that irrigation in that region influences as much as 40% of the precipitation several thousand kilometers away in some areas of East Africa. The process is driven by leaf transpiration and soil evaporation, which

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Pavement, to me, is the problem.”
—SAMUEL BRODY, professor at Texas A&M University, on the damage caused by historic flooding in Houston in April when almost 10 inches of rain fell in 6 hours, triggering flash floods. Although Houston has a long history with flooding, there’s been an upsurge in property damage and loss of life recently. Brody is blaming it on the increase in paved surfaces that has come with a significant boost in the city’s population. He and his colleagues calculated that between 1996 and 2001, the region increased its paved surfaces by about 25%, or hundreds of square miles. Since pavement is impermeable, the water has nowhere to go when the heavy rain falls. While better flood planning is necessary, Brody notes it shouldn’t be left to individual developments or neighborhoods since the rain doesn’t fall evenly over the Houston area. Research he and his colleagues conducted suggests that some solutions could involve changing building codes, elevating structures to reduce property loss, and designating vulnerable areas as protected open spaces. [SOURCE: CNBC.com]
LOOKING FOR AN EXPERT?

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LOOKING AT ENSO TO HELP PREDICT TORNADOES

Current tornado forecasting is only accurate to about seven days in advance of the storms. But a new study published in *Environmental Research Letters* suggests that regional tornado outbreaks could be predicted as much as 1–3 months ahead of time by studying patterns in the spring phases of the El Niño-Southern Oscillation (ENSO). Variability in North Atlantic sea surface temperatures also was identified as important.

Using the definition of a regional tornado outbreak as 12 or more F1-F5 “F-scale weighted” tornadoes (weighted to emphasize more intense and violent tornadoes) occurring within five days and a 200-kilometer radius, the researchers studied spatial patterns of outbreaks that occurred in springtime in the United States between 1950 and 2014 during the four different kinds of springtime ENSO phases: strong El Niños and La Niñas that linger well into springtime, and weak El Niños and La Niñas that last for only a short time after their winter peak. They discovered that each phase had a distinctive impact on tornado outbreaks, as illustrated in the figure (black dots indicate a significantly heightened risk of an outbreak).

Strong, lingering El Niño events generally are followed by limited tornado activity, except for around the Gulf Coast and central Florida in February (top left). A weak, shortened El Niño event leads to as much as a 50% increase in the odds favoring tornado outbreaks in the Upper Midwest in May (top right). When La Niña lingers into springtime and then resurges into a second-year La Niña in the fall, the probability of outbreaks in parts of the Ohio Valley, southeast United States, and Upper Midwest in April between the two La Niña years increases by almost 60% (bottom left). And when a La Niña lasts for two years and then develops into an El Niño, there is a 50% increase in the probability of an outbreak in parts of the southern United States, particularly in Kansas and Oklahoma during April of the transition year (bottom right).

The researchers noted that the two superoutbreaks of tornadoes in the South in 2011 as well as the historic 1974 Superoutbreak all occurred in resurging La Niña years.

The study found a separate connection between North Atlantic sea surface temperature variability and tornado outbreaks, as well, owing to regional forcing mechanisms with the different phases of such teleconnections as the North Atlantic Oscillation (not shown).

The study clarifies that this research does not result in seasonal springtime tornado prediction, and points out that more work is needed to build a seasonal prediction model or provide accurate predictive skill. Still, it notes that the results are quite promising.

“This is very exciting research because it can have a direct impact on saving people’s lives and minimizing damages,” notes the study’s lead author, Sang-Ki Lee of NOAA’s Atlantic Oceanographic and Meteorological Lab. “Extending our severe weather outlooks beyond seven days will give communities much needed time to prepare.” [Source: NOAA; Image Credit: Climate.gov/Will Chong (MAPP)/Alison Stevens (MAPP)]
New Portal Highlights Rising Seas

With the world’s oceans continuing to advance, “sea level change is a hot topic in climate research,” notes Carmen Boening of NASA’s Jet Propulsion Laboratory (JPL). Boening helps manage a new web portal developed by JPL that aims to bring together much of that research in one location, helping both scientists and the public keep track of the vast amount of available information.

The site, called “Sea Level Change: Observations from Space” (https://sealevel.nasa.gov), features a comprehensive overview of the current knowledge of sea level rise based on decades of research, including causes, observations, projections, and potential ways society might adapt. The site also includes an interactive data analysis function, which gives users direct access to NASA’s sea level datasets and allows them to generate charts, graphs, and maps of various data such as sea surface temperature and height anomaly. Users can also utilize this tool to forecast future conditions and hindcast past trends.

Additionally, the site includes interviews with researchers in the field, a library of published papers on sea level rise and related subjects, videos and still photos, and a glossary, and it regularly adds NASA news stories about the latest sea level research.

The new site “provides a NASA resource for researchers and a wealth of information for members of the public seeking a deeper understanding of sea level change,” says Boening. [SOURCE: Jet Propulsion Laboratory]

The Arctic Report Card

Issued annually since 2006, the Arctic Report Card is a clear, reliable, and concise source of information on the current state of the Arctic environment relative to historical records. Following record and near-record changes in sea ice in 2015 that are having profound effects on the marine ecosystem (fishes, walruses, primary production) and sea surface temperatures, the annual update for 2016, to be released in December, is projected to mark a landmark year of Arctic change.

Prepared by an international team of more than 70 scientists from 11 countries, the Arctic Report Card serves as a timely, peer-reviewed source that includes essays on air temperature; terrestrial snow cover; the Greenland Ice Sheet; sea ice; sea surface temperature; ocean primary productivity; and tundra greenness, with less frequent updates on additional topics such as ozone, permafrost, caribou, and marine mammals.

Near-surface winter 2016 (Jan-Apr) Arctic temperature differences from long-term averages (1981–2010). The entire Arctic was involved with 4-month temperature differences of greater than 4°C. (Image provided by NOAA’s Earth System Research Laboratory, Physical Sciences Division, www.esrl.noaa.gov/psd/, based on the NCEP/NCAR Reanalysis.)
Highlights of the Report Card in 2015:

- Maximum sea ice extent on February 25 was 15 days earlier than average and the lowest value on record (1979–present). Minimum ice extent in September was the fourth lowest on record. Sea ice continues to be younger and thinner: in February and March 2015 there was twice as much first-year ice as there was 30 years ago.

- Air temperatures in all seasons between October 2014 and September 2015 exceeded 3°C above average over broad areas of the Arctic, while the annual average air temperature (+1.3°C) over land was the highest since 1900.

- The 2nd lowest June snow cover extent on land continued a decrease that dates back to 1979, while river discharge from the great rivers of Eurasia and North America has increased during that time.

- Melting occurred over more than 50% of the Greenland Ice Sheet for the first time since the exceptional melting of 2012, and glaciers terminating in the ocean showed an increase in ice velocity and decrease in area.

- Walruses are negatively affected by loss of sea ice habitat but positively affected by reduced hunting pressure, while sea ice loss and rising temperatures in the Barents Sea are causing a poleward shift in fish communities.

- Widespread positive sea surface temperature and primary production anomalies occurred throughout the Arctic Ocean and adjacent seas as sea ice retreated in summer 2015.

- Terrestrial vegetation productivity and above-ground biomass have been decreasing since 2011.

Already observed in 2016 are record-setting high air temperatures for January–April and low winter sea ice extents. We anticipate that the extreme warm temperatures will have impacts throughout the Arctic system; for example, spring 2016 had reduced seal habitat, and there were major early wildfires in northern forests. Scientists are watching for possible record loss of September sea ice.

The Arctic Report Card is intended for a wide audience, including scientists, teachers, students, decision-makers, and the general public interested in the Arctic environment and science. The web-based format expands the availability of the content (www.arctic.noaa.gov/reportcard).

Impacts of Climate Extremes in Brazil

The Development of a Web Platform for Understanding Long-Term Sustainability of Ecosystems and Human Health in Amazonia (PULSE-Brazil)

by Jose A. Marengo, Luiz E.O.C. Aragão, Peter M. Cox, Richard Betts, Duarte Costa, Neil Kaye, Lauren T. Smith, Lincoln M. Alves, and Vera Reis

MOTIVATION. Amazonia has experienced “droughts and floods of the century” during the last 10 years, and this has affected humans and natural systems through direct impacts from the events as well as increased forest fires and an increased risk of diseases. There is more data than ever before to monitor and understand the impact of such climatic extremes. However, the quantity of long-term multitemporal and multisource information increases the complexity of data management and limits the ability of policymakers to act on any improved understanding of Earth system processes. Such capacity, especially in tropical countries, is critical for developing mitigation and adaptation policies to cope with the effects of climate perturbations. This is central for the objectives of the Global Framework for Climate Services (GFCS; http://gfcs.wmo.int/) established during the 2009 World Climate Conference, which was conceived to promote the sharing of science-based knowledge with decision-makers and for prioritizing sectors such as risk reduction, water, human health, and food security.

Currently, it is difficult to synthesize all available information in a comprehensive structure that enables different sectors of the society to understand the consequences of extreme events and support timely decision making. In recognition of this problem of data compilation, management, and visualization, a consortium of cross-disciplinary Brazilian and U.K. scientists, encompassing environmental, human health, and modeling backgrounds, was selected under the umbrella of the International Opportunities Fund, and jointly funded by the São Paulo Science Foundation (FAPESP) in Brazil and the Natural Environment Research Council (NERC) in the United Kingdom to enhance the knowledge in environmental sciences directly applicable to policy decisions.

A key result of this cooperation is the ongoing development of PULSE-Brazil, a Platform for Understanding Long-term Sustainability of Ecosystems and human health, specifically applied to Brazil. PULSE-Brazil (www.pulse-brasil.org/tool/) was conceived as a platform to assimilate available climate, environmental, and human health data and translate this information into user-friendly outputs such as graphs and maps, thereby 1) allowing the establishment of a science-policy knowledge interface about the impacts of climate variability and change on society, 2) increasing public awareness of these issues, and 3) informing the development of adaptation and risk-management strategies.
This initiative is especially relevant for coping with the targets of the Brazilian National Plan for Climate Change (BNPCC; www.mma.gov.br/clima/politica-nacional-sobre-mudanca-do-clima/plano-nacional-sobre-mudanca-do-clima), established in 2007 by the government. Elaborated upon by federal and state governments, academics, and civil society, this plan encompasses several aspects of climate change science and dissemination of information, including opportunities for mitigation; impacts, vulnerability, and adaptation; research and development; and education, training, and communication. BNPCC is aligned with the responsibilities assumed by Brazil within the United Nations Framework Convention on Climate Change (UNFCCC; http://unfccc.int/2860.php).

To meet the objectives of the PULSE-Brazil platform, three aspects of the development process require attention: 1) the interaction between scientists and policymakers for designing and producing PULSE-Brazil, 2) the characteristics of the platform itself, and 3) the applicability of the platform for analyzing the impacts of climate extremes on human and natural systems in Amazonia. This paper summarizes the strengths and weaknesses of the whole process, and provides insight for future initiatives.

**DESIGN AND PRODUCTION OF PULSE-BRAZIL.** Scientific research is virtually constrained by funding opportunities, which often are focused on disciplinary priorities. This in turn limits potential transdisciplinary collaboration. PULSE-Brazil started with a cross-disciplinary academic design and production model, aimed at supporting decision-making (Fig. 1a). A series of PULSE meetings between U.K. and Brazilian scientists was undertaken in 2012 to design the platform. The state of Acre, located in western Amazonia, was identified as a key pilot partner for PULSE-Brazil, in part because of its governmental interest in environment sustainability, and also because the state has suffered a number of damaging climatic extremes, such as droughts and floods, since 2005, increasing the need to prepare for and adapt to climate change. In 2013, at a meeting held at the Met Office (UK), an introduction to the implications of extreme climate events in Acre was presented by a team of PULSE scientists from the Oswaldo Cruz Foundation (FIOCRUZ) under the Brazilian Ministry of Health and the National Institute for Space Research (INPE) under the Brazilian Ministry of Science, Technology and Innovation. In response, current policy experiences were described by a group of Acre officials that were present and active at the meeting. Two main sets of information were identified at this meeting as critical for policy decisions in Acre state: 1) the combined effects of climate and land-use changes on droughts, with consequences for the incidence of fires, floods, and human health, and 2) the direct impacts of recent hydrological extremes in Amazonia on human health. Moreover, this meeting interestingly revealed that tropical governments not only have a need for accessing long-term Intergovernmental Panel on Climate Change (IPCC; www.ipcc.ch/-type projections, but also a growing demand for shorter-term information on climate extremes to assist their decision-making processes.

![Fig. 1. Conceptual models identified for designing and producing decision-support tools, based on the PULSE-Brazil experience. (a) Idealized model—proposed by scientists to research council and followed during the initial phase of the project. (b) Used model—jointly conceived by scientists and policy makers. (c) Proposed model—for future initiatives, aiming to enhance the coherence between science knowledge and policy needs and optimize funding input for long-term maintenance of proposed decision-making support tools.](image)
This valuable contribution by government officials required a change of the PULSE-Brazil model to a participatory concept, adopting a scheme where the design of the tool concept followed scientific standards, but its implementation allowed the interaction between stakeholders and scientists, in a coproduction fashion (Fig. 1b). Facing this new challenge, scientists and policymakers agreed to a pilot testing period for the PULSE-Brazil platform at the end of 2013, based on the communicated needs of Acre state officials.

**THE PULSE-BRAZIL PLATFORM.**
The PULSE-Brazil platform was designed as a web application tool developed using the latest open-source technologies to create a flexible visualization and analysis tool (Fig. 2). This platform has a number of key components to power it: a) HTML5 has good browser cross-compatibility and the ability to make responsive websites for different types of devices, including mobile devices; b) GeoServer is an open-source server for sharing geospatial data. Designed for interoperability, GeoServer publishes data from any major spatial data source using open standards. For PULSE, it allows for the display and interrogation of more than 5,000 highly detailed municipalities and their associated data; c) Open Layers, which creates interactive maps, including polygon formats for displaying state and municipality boundaries as well as gridded data for representing climate models and observation data; and d) d3.js, which is an open-source JavaScript library for manipulating documents based on data, allows developers to create unlimited visualizations and graphs. PULSE-Brazil provides visualization of spatial and temporal information offering interactive querying and data downloads.

Importantly, these technologies are all freely available. Although no support is available from large geographic information systems (GIS) companies such as ESRI and Oracle, copious support is accessible online. Unlike many other platforms or GIS that allow climate data visualization and analysis but require expertise to operate, PULSE-Brazil was designed to be a ready-to-use visualization tool with intuitive query features, and available for access through the World Wide Web. The data are prerendered, accelerating visualization, and a client-side design uses the power of a user’s computer for processing and creating interactive graphing. The client-side design makes the system scalable for hundreds of concurrent users.

Based on the latest scientific information and clear demands from policymakers, the PULSE-Brazil tool was initially populated with: a) climate observations up to 2012 from the Climatic Research Unit (CRU; www.cru.uea.ac.uk/data), University of East Anglia, at a 1°×1° spatial resolution; b) climate projections from the CMIP5 archive, located at http://cmip-pcmdi.llnl.gov/cmip5/ (and as used in the IPCC 5th Assessment), where the PULSE-Brazil Platform displays decadal-mean maps showing changes in temperature, precipitation, and runoff relative to 1961–90 values; c) river-level observational datasets for the Brazilian state of Acre covering the

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**Fig. 2.** Main visualization features of the PULSE-Brazil platform, including (a) the dataset menu, gridded past and projected climate, and human health data. Also shown are example graphic representations of (b) historical climate, (c) human health, (d) river levels for Acre state, and (e) CMIP5 climate projections.
past 40 years; and d) human health data from the Brazilian Unified Health System (SUS; www2.datasus.gov.br/DATASUS/index.php) for regional hospitalization data for key climate- and environmentally sensitive diseases: malaria, dengue fever, diarrhea, leptospirosis, and respiratory diseases.

VISUALIZING CLIMATE IMPACTS USING PULSE-BRAZIL. The Amazonian state of Acre suffered two droughts (2005 and 2010) leading to water shortages, forest fires, and a proliferation of diseases. Using the visualization capacity of the PULSE-Brazil tool, we tested whether the impacts of the 2010 drought in Acre state could be clearly identified.

Exploring the gridded climate data, the occurrence of positive temperature anomalies up to 2 degrees in the southeast flank of the state during September 2010 is clear (Fig. 3b). The high temperatures occurred in parallel to negative rainfall anomalies across the state (Fig. 3c). Shifting through the data menu, the PULSE-Brazil user is able to conclude that this coincided with the occurrence of malaria reaching more than 100 cases per 10,000 inhabitants in the northwest portion of Acre (Fig. 3d). In Brazil, studies show that more than 90% of malaria cases are in Amazonia. Dengue fever, conversely, is more concentrated in the municipality of Rio Branco with 20 to 50 cases per 10,000 inhabitants (Fig. 3e). It is well established that temperature affects the dengue...

Fig. 3. Climate and health patterns for September 2010 in Acre state southwest Amazon, defined by the red box (a). Panels (b) and (c) show spatially explicit temperature (°C) and rainfall (precipitation, mm) anomalies, respectively. Panels (d), (e), and (f) present the recorded cases (in numbers of cases per 10,000 inhabitants) for malaria, dengue fever, and diarrhea, respectively. Polygons represent the municipalities of Acre state. Panels (g) and (h) show time series of historical temperature and rainfall anomalies during September, respectively. Note the extreme anomalies in 2010.
viruses and vector populations. Rainfall is the main variable that influences habitat availability for the dengue mosquito, *Aedes aegypti*. Diarrhea seems to be widely spread across the state, even during the dry season (Fig. 3f).

Finally, flipping through the menu and clicking over Acre state, users can create a graphical summary of historical temperature and rainfall anomalies for the month of September (Figs. 3g and 3h, respectively). This can be done for any historical or projected dataset included in the PULSE-Brazil platform.

**STRENGTHS AND WEAKNESSES.**

The information disseminated through the PULSE-Brazil web portal provides valuable monthly-to-decadal-scale climate, ecosystem, and human health information for scientists and society. A strong feature of this platform is its capacity to display a wide range of spatially explicit regional datasets from multiple sources in a single environment. This characteristic of the tool, we believe, makes it especially useful in the context of the GFCS, the BNPCC, and its contributions to the UNFCCC.

PULSE-Brazil is not yet a complete data-rich tool for all Brazilian regions. However, the platform can provide a set of municipality-, state-, and national-level information without having to contact each individual data provider. This is particularly important for health data, as any data produced by Brazilian government institutions must become publicly available following the 2011 Information Access Law (Law 12.527/2011). The dialogue between scientists and policymakers is essential for the coproduction of platforms such as PULSE-Brazil. Examples of specific user-driven contributions are the introduction of river-level information for Acre state (Fig. 2d) and the fire risk dataset that will be incorporated in the near future.

The PULSE-Brazil database structure is concentrated in a single institute, the UK Met Office. Therefore, a key challenge for the longevity of this initiative is to decentralize the platform by identifying host institutes with necessary resources for maintaining and upgrading the system. A potential strategy for future developments is to shift the whole model of this type of initiative toward a codesign and coproduction process (Fig. 1c), with well-established commitments from end users.

**PERSPECTIVES.**

The result of PULSE-Brazil is a web application that effectively visualizes many different modeling and observed datasets, in gridded and graphic formats, promoting a broader understanding of the impacts of climate on human health and ecosystems, supporting policymaking decisions to lessen these impacts. A close interaction between scientists and policymakers in the Brazilian state of Acre has resulted in the coproduction of a platform with customized features, without affecting the broad, national-level scope of the tool.

The PULSE-Brazil team is now expanding the health data beyond Acre state to cover all 5,570 municipalities in Brazil; including active fire data from MODIS (collection 5 Global Monthly Fire Location Product, MCD14ML; https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms); and updating the system with regional climate model outputs. Additionally, PULSE-Brazil is being applied in the littoral city of Santos, in the State of Sao Paulo, where we are investigating coastal vulnerability to sea level rise, extremes, and also the impacts of climate variability and change on human health in this city, particularly the spread and projected impacts of dengue fever. Ultimately, PULSE-Brazil scientists will continue to seek strong institutional partnerships with a view to expanding this initiative to other tropical nations.

**ACKNOWLEDGMENTS.** This work was funded by the joint FAPESP 2011/51843-2 and NERC NE/J016276/1 International Opportunities Fund. PULSE-Brazil development is also funded by the FAPESP grant (2012/51876-0) under the Belmont Forum Cooperation Agreement. Marengo and Aragão thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for their Research Productivity Fellowship.

**FOR FURTHER READING**


Hazzard, E., 2011: Openlayers 2.10 beginner’s guide. Packt Publishing Ltd.


Data assimilation (DA) integrates computer simulations and real-world observations based on statistical mathematics and dynamical systems theory, and plays a central role in numerical weather prediction (NWP). As computing and sensing technologies advance, DA will deal with “big simulations” and “big data.” Here we focus on rapidly changing convective weather and explore a future direction of two orders of magnitude more rapid weather forecasting by innovating what we call “big data assimilation” (BDA) technology. Tremendous efforts have been devoted to convective-scale NWP and radar DA, including the U.S. effort on the “Warn-on-Forecast” project (Stensrud et al. 2009; 2013), which has been pioneering rapidly updated NWP to be used for warnings about convective-scale hazards. Sun et al. (2014) provided a comprehensive review on this subject with a rich body of literature. Extending a wealth of previous studies, this article presents the concept of BDA research and the first proof-of-concept results of a real high-impact weather case, exploring 30-min forecasts at 100-m grid spacing refreshed every 30 s—120 times more rapidly than hourly updated systems. This revolutionary NWP is only possible by taking advantage of the fortunate combination of Japan’s most advanced technological developments: the 10-petaflops (floating-point operations per second) “K computer” and Phased Array Weather Radar (PAWR; Ushio et al. 2014; Yoshikawa et al. 2013). The science and analytics of big data, typically characterized by four “big V’s” (volume, variety, velocity, and veracity), are growing rapidly, and BDA is one of the first two projects awarded by the Japanese government strategic funding program started in 2013 on general big data applications.

In contemporary weather forecasting, radar observations and NWP play an essential role in real-time monitoring and short-term prediction of severe weather. The widely used parabolic-antenna radar observes rain intensity along a curvilinear beam track. The radar is rotated, and changes the azimuth and elevation angles to capture the whole sky typically in 5 min for 15 elevation angles. Also, typical convective-scale NWP updates forecasts every hour for the next 0 (10) hours at O(1)-km grid spacing. However, convective weather systems evolve quickly in 5 min and undertake a nonlinear evolution. The current NWP systems that could possibly use all 5-min radar data at the highest frequency may still be far from sufficient to precisely represent individual convective activities.

Here we explore what the highest-end, next-generation supercomputing and sensing technologies can do at their full capacity, pioneering the future of weather forecasting for the next 10 years. The cutting-edge PAWR implemented in Osaka, Japan, in...
summer 2012 is capable of observing 100 elevation angles within only 30 s and produces about 100 times more data than the widely used parabolic-antenna radar. Unlike the every-5-min data, the every-30-s data show the continuous evolution of convective weather systems, and we may reasonably assume a linear evolution in 30 s at convective scales (Fig. 1).

Also, the highest-end supercomputers to date with $O(10)$-petaflops capability enable high-precision weather simulations at $O(10)$-m grid spacing, or even smaller.

To fully take advantage of the large-volume and high-velocity big data from the most advanced simulations and sensors, we propose BDA innovation. BDA aims to refresh 100-m-mesh weather forecasts every 30 s, orders of magnitude faster and more precise than the typical operational hourly updated systems at $O(1)$-km grid spacing, leading to an $O(10)$-minute-lead

Fig. 1. (a) PPI reflectivity (dBZ) at the 8.152° elevation angle (approximately 4–6 km in the 25–45-km ranges) at 1500 JST, 13 Jul 2013 from the Osaka phased array weather radar. (b)-(l) Every-30-s frames of reflectivity vertical cross sections along the line shown in (a).
early warning for sudden local severe weather. BDA is also a leap by an order of magnitude over the cutting-edge research which refreshes about 1-km-mesh forecasts every several minutes (e.g., Aksoy et al. 2009; Stensrud et al. 2013; Yussouf et al. 2013).

We developed a prototype BDA system, the workflow starting with 100 parallel simulations or ensemble runs of 100-m-mesh NWP (“100M”) for 30 s using the Japan Meteorological Agency (JMA) nonhydrostatic mesoscale model (NHM; Saito et al. 2006). JMA runs the NHM operationally at 5-km and 2-km grid spacing—50 and 20 times coarser than the BDA system, respectively. The simulation domain is chosen to be a 120-km-by-120-km square centered at the Osaka PAWR, covering the 60-km range of the Osaka phased array weather radar. Color shading indicates elevation (m) except for light blue showing the ocean areas.

![Fig. 2. (a) Computational domain for the outermost 15-km-resolution NHM-LETKF experiment, (b) computational domain for outer 1-km NHM, and (c) computational domain for the innermost 100-m-resolution BDA system with the circle indicating the 60-km observation range of the Osaka phased array weather radar. Color shading indicates elevation (m) except for light blue showing the ocean areas.](image)

A single 30-min simulation takes about 15 s for the total 7.1 $10^{15}$ floating-point operations of the 100 parallel NHM runs and LETKF, feasible for the 30-s cycling processes considering the additional time for data transfers between the NHM and LETKF, although the full-capacity experiment is a subject of future research. Compared with 1KM, BDA takes $O(10^3)$ and $O(10^2)$ more computations for the forecasts and LETKF, respectively. These are consistent with an estimate that $O(10)$ times more resolution requires $O(10^3)$ given by the arithmetic average of the 100 states or simply the ensemble mean, is used to initialize a 30-min simulation. Here, the PAWR data are preprocessed by the newly designed quality control algorithm that takes advantage of the PAWR’s unique, high vertical and temporal resolution (Ruiz et al. 2015). Attenuated echoes are identified and rejected by quality control. For comparison, we also developed a reduced-resolution system at 1-km grid spacing (simply “1KM”).

We have run the prototype BDA system with up to 3,072 nodes of the Japanese 10-petaflops K computer and measured the computational amount as shown in Table 1 (see appendix A in the electronic supplement). With the full capacity of 88,128 nodes (705,024 cores) of the K computer at a typical 5% computational efficiency (i.e., 5% of the 10-petaflops peak performance, effectively 5 $10^{14}$ flops), it takes about 15 s for the total 7.1 $10^{15}$ floating-point operations of the 100 parallel NHM runs and LETKF, feasible for the 30-s cycling processes considering the additional time for data transfers between the NHM and LETKF, although the full-capacity experiment is a subject of future research. Compared with 1KM, BDA takes $O(10^3)$ and $O(10^2)$ more computations for the forecasts and LETKF, respectively. These are consistent with an estimate that $O(10)$ times more resolution requires $O(10^3)$

<table>
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<tr>
<th>Grid spacing</th>
<th>100 m</th>
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<td>$5.8\times10^{12}$</td>
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<tr>
<td>Data assimilation</td>
<td>$4.5\times10^6$</td>
<td>$76\times10^{12}$</td>
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<tr>
<td>A single 30-min simulation</td>
<td>$1.6\times10^6$</td>
<td>$3.5\times10^{12}$</td>
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more computations due to an increased number of grid points both for forecasts and LETKF, and $O(10)$ times more computations for forecasts due to a shorter time step.

The prototype BDA system was tested in a retrospective high-impact weather case that occurred on 13 July 2013, when Kyoto, Japan, had floods and a number of power outages due to severe lightning strikes. The convective rain system was well captured by the Osaka PAWR (see animated three-dimensional visualization in the electronic supplement). First, we have run the “NODA” experiment, in which the BDA system was initialized at 1500 Japanese Standard Time (JST: UTC + 9 hours) and was run for 10 min without observation data input. The 100-m-mesh initial conditions are generated by downscaling an independent 15-km-resolution NHM-LETKF system (see appendix B in the electronic supplement for details). Therefore, NODA contains information only on larger-scale convective instability but not on individual convective cells, which are typically resolved at $O(1)$-km grid spacing or smaller. Next, we ran the 100M experiment, exactly the same as NODA but with all 30-s PAWR data used. We also ran the 1KM experiment with both model and observations reduced to 1-km resolution. We assimilated weak echoes as “zero precipitation” (Aksoy et al. 2009; Yussouf et al. 2013).

We can see that both 100M and 1KM quickly become closer to the PAWR observations (Fig. 3). Figure 3 shows sawtooth patterns that are typical for cycling DA, for 100M and 1KM in the initial 10 min (white background), indicating that the errors are reduced by assimilating the PAWR data every 30 s. After the eighth DA step, or 1504 JST, the root-mean-square errors (RMSE) relative to the PAWR’s observed reflectivity reach the asymptotic level of about 7 dBZ for 100M (Fig. 3a). 1KM shows about twice as large RMSE for reflectivity, mainly because the 1KM model data cannot fit the higher-resolution PAWR data at about 100 m. For Doppler velocity, the RMSE drops more quickly for 100M than for 1KM, but at 1510 JST the RMSE are similar around 2.3 m s$^{-1}$; that is, the observed radial velocity field is smoother, and 1KM model data can fit as well as 100M. We have run longer DA cycles and found that the 100M RMSE did not keep increasing (not shown).

The three-dimensional rain distribution captured by PAWR reflectivity at 1510 JST (Fig. 4a–h) shows very good agreement between 100M and the actual PAWR observation, while NODA shows only a broad precipitation pattern partly because of the averaging of widely dispersed ensemble runs. We find that 100M presents the three-dimensional structures of individual convective cells almost identically to the actual observation (Fig. 4g,h). 1KM agrees generally well, but has smoother patterns and missing details (Fig. 4b,f). While PAWR observations provide only reflectivity and Doppler velocity, the model produces physically consistent meteorological fields (Fig. 4j,k). Namely, strong heating in the convective center at around 3–6 km due to latent heat release from water and ice condensation is associated with a strong upward motion of about 10 m s$^{-1}$ from 2 km to the tropopause. Cooling occurs near the ground due to rainfall behind the heating convective center.
Again, 1KM shows only smooth patterns. 100M's higher resolution can resolve smaller-scale details that may be relevant to local severe phenomena. For example, 100M simulates more detailed structures of hydrometeors with higher peak values of snow and graupel contents (Fig. 5, blue and red shades) accompanied by stronger updrafts (Fig. 5, black contours), suggesting a higher potential of lightning strikes. Also, Figs. 5e and 5f show significant differences, so that large rainwater content (green shades) reaches the ground in 100M but not in 1KM.

Representing these complete meteorological fields beyond what is observed is essential to improve forecasts for the next 30 min (Fig. 3, after 1510 with yellow background). Compared with NODA, both 100M and 1KM indicate strong reflectivity, more similar to the observed reflectivity in the 10, 20, and 30-min forecasts, although the forecast skill drops quickly (Fig. 6). 1KM and 100M are generally similar, and if we focus on larger-scale structures that the 1-km NWP can resolve (typically larger than 5- to 10-km scales), 1KM is useful as suggested by the previous studies (e.g., Aksoy et al. 2009; Stensrud et al. 2013; Yussouf et al. 2013). 100M includes small-scale structures, though not necessarily close to the observations. 1KM has about twice as large RMSE for reflectivity at the initial time, but the RMSE grows slowly and becomes similar to 100M around 1520 JST (Fig. 3a). Namely, the 100M's small-scale structures are close to the observations at the initial time but evolve rapidly and lose predictability after 10 min. The small-scale structures may be essential in the development of hazardous phenomena, and the skill in the initial 10 min may be critical for successful evacuation of those at risk.

Also, 100M potentially resolves local peak quantities. If we verify the 30-min accumulated rainfall amount from 1510 to 1540 JST in Kyotanabe, Japan...
(Fig. 6, cross marks), 100M shows 23.95 mm, very close to the JMA gauge observation (20.5 mm), while 1KM indicates only 0.95 mm and none for NODA. No other station from the JMA gauge network reported a significant rainfall greater than 10 mm for this 30-min period due to this event, and a thorough verification with more cases is beyond the scope of this article.

Both 100M and 1KM tend to overproduce the strong reflectivity regions east of the actual observed echoes and may lead to a false alert (Fig. 6). The simulated reflectivity shows an increasing bias trend: at 1540 JST, 100M (1KM) shows the bias of 17.24 (21.29) dBZ relative to the PAWR observations. Also, Fig. 3b shows a rapid growth of the forecast error for Doppler velocity in the first 5 min. 100M shows a more rapid error growth than 1KM, and loses the skill completely after 10 min, even worse than NODA. These results may be related to systematic model errors, particularly in the microphysics schemes, and a dynamical imbalance caused by the 30-s update cycles. The current NWP systems have not been designed or tested with such rapid updates and dense PAWR observations, and NWP system developments for frequent updates and \(O(100)\)-m grid spacing or smaller would be essential. Previous studies (e.g., Aksoy et al. 2009; Stensrud et al. 2013; Sun et al. 2014) also suggested that we can provide very accurate analyses, but the forecasts resulting from these analyses tend to lose predictability very rapidly. It is critically important to improve the forecasts for practical applications, and this remains a subject of future research.

Here we showed the general concept of BDA and the first proof-of-concept case study. Future work includes improving the forecast skill with more case studies and enhancing the computational performance with the full capacity of the K computer with nearly a million CPU cores. Improving microphysics and other components of the NWP model for severe weather prediction is a grand challenge. Also, it is important to explore what benefits we can get from the 100-m-mesh 30-s-update BDA for different types of high-impact weather cases at the cost of \(O(10^2)\) more computations than a 1-km-mesh counterpart. Moreover, we have another big data source for BDA: the JMA’s new geostationary meteorological satellite Himawari-8 that started full operations.
in July 2015 with full-disk observations every 10 min and simultaneous limited area observations every 2.5 min and even every 30 s. Radars capture raindrops, but not smaller cloud droplets, which satellite imagery can capture at an earlier stage of convective development. Exploring an effective use of the high-frequency geostationary imagery data from Himawari-8 for further improvements of convective predictability is an important focus of BDA research.

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**Fig. 6.** Similar to Fig. 4a–d, but for 30-min single deterministic forecasts initialized from the ensemble means of (a, e, i) 10-min NODA forecast, (b, f, j) 1KM analysis, and (c, g, k) 100M analysis, and for (d, h, l) actual radar observation. The top, second, and third rows show 1520, 1530, and 1540 JST, corresponding to 10-, 20-, and 30-min deterministic forecasts initialized from the corresponding ensemble means, respectively. The cross marks indicate the JMA gauge station at Kyotanabe.
FOR FURTHER READING


The atmosphere would be a much simpler system if it did not contain water vapor—but it would also be far less interesting to atmospheric scientists and meteorologists, not to mention less hospitable to life. The presence of a trace substance—water—that exists as a gas, a liquid, and a solid under the range of typical atmospheric conditions, changes everything: water vapor is a primary greenhouse (infrared active) gas, the latent heat release in cloud convection fundamentally changes the temperature structure of the atmosphere, and of course the presence of clouds and precipitation themselves profoundly alter the radiative balance of Earth (Durran and Frierson 2013; Stevens and Bony 2013). The simplest radiative equilibrium models do a surprisingly poor job of capturing Earth’s mean temperature when water vapor and clouds are not included at least in some simplified way. Of course the hydrological cycle depends crucially on the evaporation of water from the warm oceans of Earth and the eventual condensation of water vapor to generate precipitation; and one of the key pathways for precipitation formation depends on the differential equilibrium vapor pressure of liquid and solid phases of water. It is therefore central to the teaching of atmospheric physics to correctly convey the concept of phase equilibrium. Indeed, the Clausius–Clapeyron equation that expresses the temperature dependence of equilibrium water vapor pressure on temperature could be considered one of a handful of equations that an undergraduate meteorology student should really internalize, right up there with the hydrostatic equation and equations for geostrophic balance. It is our experience, though, that the concept of equilibrium vapor pressure and its temperature dependence is deceptively subtle and challenges even the brightest of students [and sometimes their teachers; see Bohren and Albrecht (1998) for a discussion of some of the more infamous pitfalls]. In this essay we introduce a demonstration experiment that provides a vivid, mechanical analogy for the concepts of evaporation,
condensation, and the temperature dependence of equilibrium vapor pressure. The demonstration is useful for conveying a conceptual understanding of these concepts but also can illustrate the essential concepts underlying the functional form of the most common expression for equilibrium vapor pressure.

At a given temperature, the rates of molecular exchange across the liquid–vapor interface must differ for a net transfer of matter to occur between the phases. We speak therefore of net evaporation (when the flux of molecules leaving the liquid exceeds the rate molecules reenter the liquid) and net condensation (when the condensation flux exceeds the evaporation flux). It is important to distinguish between the practical usage of the terms (evaporation and condensation) and the physical processes of molecular exchange across the liquid–vapor interface, which occur simultaneously. When the rate that molecules escape from a liquid exactly equals the rate of return, no net transfer of matter occurs, and the system is said to be in equilibrium, a dynamic steady state. Knowing the precise point of equilibrium is of course key to distinguishing the conditions for net evaporation and net condensation. The equilibrium concentration of vapor in contact with the liquid surface at a particular temperature is unique to the substance in question. Here, we focus on water and use the term “vapor pressure” as the measure of water vapor concentration (through the ideal gas equation) that maintains phase equilibrium. We wish to explore the nature of this equilibrium state and how the vapor pressure varies with temperature.

The equilibrium state is intimately linked to the process by which molecules leave the liquid state. Molecules in the liquid surface escape only if they acquire kinetic energies large enough to break the bonds holding them to neighbors. The observed vapor densities therefore tell us something about the magnitudes of the cohesive bonding energies. Whereas a weakly bonded condensate (e.g., a light alcohol) evaporates readily under normal conditions and exhibits a large vapor pressure, a strongly bonded liquid (e.g., mercury) evaporates only slowly and yields relatively low concentrations of molecules in the gas phase even at elevated temperatures. Water is a substance whose molecules are bound to each other with intermediate strength through hydrogen bonding.

Detailed explanations of molecular phenomena are important in the sciences and engineering, particularly at the university level. Analogies can be valuable aids to instruction, in part because they highlight key features of the underlying physics, and in part because they help students visualize scales not sensed by humans. Mathematical analogies abound in technical fields because they capture essential features of the physics and offer opportunities for detailed quantitative analysis. Maxwell’s kinetic theory of gases, for instance, while still serving as a cornerstone of theoretical physics, gently introduces new students to the molecular world and to the rigors of statistical mechanics. Physical analogies, while not capable of the precision provided by mathematical models, serve to bring the invisible microscopic world directly to students through demonstrations and experimentation. Physical analogies have been used, for instance, by Prentis (2000) to illustrate how mechanical systems with “motorized molecules” can be described well by Boltzmann statistics when using the ergodic hypothesis of statistical mechanics. Their two-level “Boltzmann machine” utilizing multiple balls is of particular relevance to our study of vaporization, which is modeled with a vibrating plate containing a depression and a countable number of metal balls. However, whereas Prentis varied the potential energy between the levels while keeping the mechanical equivalent of temperature fixed, we suggest that evaporation is best modeled as a system in which the potential (i.e., “bond”) energy is fixed while the degree of mechanical agitation (“temperature”) is varied. In both studies, the important thermodynamic and statistical–mechanical condition of temperature uniformity throughout the system has been maintained.

This paper describes a mechanical system developed for use in the teaching of atmospheric physics. We use it as a way of introducing students to the growth and evaporation of cloud drops, for which a clear understanding of equilibria between phases is imperative. We attempt here to draw parallels between the classical Clausius–Clapeyron equation (which describes the dependence of vapor pressure on temperature) and the escape of balls from a gravitational potential energy well. We first review essential theoretical principles before describing the physical system and the data derived from it. Water is the substance of most atmospheric relevance and the focus of the discussion here, but the principles are general and apply to any volatile liquid or solid. This demonstration helps answer such questions as “What causes vapor pressure to increase with temperature?” and “What physical principles determine the form of the curve describing equilibrium vapor pressure versus temperature?”

**The Boltzmann Factor: Vapor Pressure and a Mechanical Analog.**

A molecular interpretation via the Boltzmann equation (see the sidebar for an overview) provides a compelling perspective for interpreting the temperature...
dependence of water vapor pressure. Conceptually, it is a struggle between water molecules in the liquid state effectively trapped in a depression of potential energy (“potential well”) of magnitude $l_{\text{v}}$ and the random thermal energy $k_{\text{B}}T$ that occasionally allows molecules to escape to the vapor. To first approximation, $l_{\text{v}}$ is the binding energy per molecule. [The correction due to expansion that is needed to convert binding energy to enthalpy, e.g., shown by Baierlein (1999), section 12.3, is neglected here for reasons of pedagogical simplicity.] Binding energy is essentially the potential energy, due to Coulomb or other intermolecular forces, that must be overcome to extract a water molecule from the condensed phase. Indeed, the latent heat of evaporation of water ($L = 45$ kJ mol$^{-1}$) when converted to molecular units is $l = 0.47$ eV. This value is strikingly close to twice the energy of a hydrogen bond ($\varepsilon_{HH} = 0.24$ eV) between two water molecules in the liquid phase. The ratio $l/\varepsilon_{HH} = 1.9$ provides a rough estimate of the average number of hydrogen bonds per molecule in liquid water that must be broken for a water molecule to escape the bound, liquid state and enter the unbound, gas phase. How does this binding energy compare to the thermal energy in the Boltzmann factor? At room temperature $k_{\text{B}}T \approx 0.025$ eV, so we note that $l \gg k_{\text{B}}T$, which shows via the Boltzmann factor that the fraction of molecules escaping the liquid (i.e., the fraction of molecules having energy equal to or greater than $l$) is small.

This same molecular interpretation of evaporation also explains the tendency for the rate of evaporation and hence vapor pressure to increase with temperature. Whereas classical thermodynamics shows this tendency to stem from the relative changes of entropy and volume across the phase boundary, it is equally valid to see the increase as arising from the need for the molecules to overcome an energy barrier: the enthalpy of phase change $l_{\text{v}}$. Higher temperatures lead to larger molecular kinetic energies and higher probabilities of molecules in the liquid surface being able to break the bonds holding them to liquid-phase neighbors. This larger evaporation flux must be balanced, in equilibrium, by a larger impingement flux, which arises in turn from a larger concentration of vapor over the liquid surface. Such a kinetic viewpoint is consistent with chemical kinetics and Boltzmann statistics, as seen by taking the logarithm of Eq. (SB5):

$$\ln \left( \frac{p}{p_0} \right) = \ln A - \frac{l_{\text{v}}}{k_{\text{B}}T}. \quad (1)$$

Figure 1 shows the same data for water as from Fig. SB1, now plotted as the ratio of vapor pressures versus the reciprocal of temperature. The slope of the line allows one to calculate the latent heat of evaporation (approximately the energy needed to break two hydrogen bonds in the liquid). Such macroscopic measurements thus tell us how strongly the molecules must be joined to neighbors. So, at its most basic level, evaporation is simply a result of random thermal agitation of molecules in liquid water resulting in a lucky few near-surface molecules getting jostled in just the right way to gain enough kinetic energy to exceed the binding energy and so escape from the liquid and enter the vapor phase. Simply because molecules in a liquid are embedded in a potential well (roughly equal in magnitude to the latent heat of evaporation $l_{\text{v}}$), the vapor pressure must increase with increasing temperature, again in accord with the Boltzmann factor.

This recognition that molecules in a liquid effectively reside in a potential energy well imposed by the electrical forces holding them to neighbors serves as the inspiration for our mechanical demonstration. Evaporation is here made visible by replacing the molecules with small metal balls and the electric potential well with a gravitational potential well. The mechanical demonstration consists of a horizontally oriented metal plate with a central depression (the “well”) that serves to represent the liquid state as a “mean field” of the electrical binding energy. Forced vibrations of the plate serve as the analog of thermal energy and cause a few of the balls in the well to jump up to the flat upper level (see Fig. 2). The number of particles in the “gas” phase (level 2) compared with that in the “liquid” phase (level 1) can then be written as $N_2/N_1 = \exp(-\varepsilon_{v}/k_{\text{B}}T)$, where $\varepsilon_{v}$ is the gravitational potential energy difference. Now we also need to recognize that temperature per se has little meaning in a mechanical analogy. We therefore replace thermal energy $k_{\text{B}}T$ with a mean mechanical kinetic energy $E_{\text{kin}}$. Normalization of the number densities to a reference state allows us to develop an equation that is similar in form to the integrated Clausius–Clapeyron equation. When we designate the reference condition as $E_{\text{kin},0}$ (analogous to $k_{\text{B}}T$ in a thermal system), the normalized ratio of densities in the “vapor” state (level 2) is expressed as

$$\frac{N_2(E_{\text{kin}})}{N_1(E_{\text{kin},0})}_{\text{mechanical model}} \approx \exp \left( -\frac{\varepsilon_{v}}{E_{\text{kin}}/E_{\text{kin},0}} \right). \quad (2)$$

Equation (2) is the relationship used to analyze the data from our mechanical analogy. This ratio of two Boltzmann factors is strikingly similar to the normalized concentration ratio one obtains from the thermodynamic treatment [Eq. (SB5)]:

$$\ln \left( \frac{p}{p_0} \right) = \ln A - \frac{l_{\text{v}}}{k_{\text{B}}T}. \quad (1)$$
The term “vapor pressure” as used here is a partial pressure of the gaseous component of interest in equilibrium with its pure liquid. Vapor escapes from a unit surface of liquid with a rate that increases with increasing temperature, a fact reflected in the higher vapor pressures and larger vapor densities at higher temperatures. The Clausius–Clapeyron equation, derived from the principles of classical thermodinamics, relates an increase in vapor pressure \( p \) with temperature to the difference in entropy relative to the difference in specific volume between vapor and liquid. Ultimately, this can be written approximately as

\[
\frac{d \ln p}{dT} = \frac{L_v}{RT^2}, \tag{SB1}
\]

where \( L_v \) is the molar latent heat and \( R \) is the gas constant. Integration of Eq. (SB1) over a modest range such that variations in \( L_v \) can be ignored gives a dependence on temperature that can be written as an Arrhenius relationship:

\[
\frac{p(T)}{p_0} = A \exp \left( \frac{L_v}{RT} \right). \tag{SB2}
\]

Here \( p_0 \) (=611 Pa for water) is the vapor pressure at the ice point \( T_0 = 273.15 \) K, and \( A = \exp(L_v/RT_0) \).

As seen in Fig. SB1, the vapor pressure of water increases exponentially with temperature, in accord with Eq. (SB2), which suggests that water molecules escape with increasing frequency as the temperature is raised.

Equation (SB2) is obtained from classical thermodynamics, as commonly developed in atmospheric physics texts (e.g., Wallace and Hobbs 2006, p. 98; Lamb and Verlinde 2011, p. 134). A molecular perspective interprets the exponential expression as a Boltzmann factor, a concept already familiar to atmospheric scientists in the guise of the hydrostatic balance equation for an isothermal atmosphere:

\[
\frac{p_{\text{sat}}}{p_0} = \exp \left( \frac{-mgz}{k_B T} \right). \tag{SB3}
\]

where \( p_{\text{sat}} \) is the total pressure (subscript “total” to differentiate from vapor pressure), \( p_0 \) is the surface pressure (at height \( z = 0 \)), \( m \) is the mass of a gas molecule, \( g \) is the gravitational acceleration, and \( k_B \) is the Boltzmann constant (the molecular gas constant). The hydrostatic balance equation is typically derived by equating the pressure difference across a horizontal slab of air of thickness \( dz \) to the weight of the slab per unit area. One readily sees that the numerator of the exponential term \( (mgz) \) is nothing more than the gravitational potential energy of the gas molecules above the surface.

This result can be generalized to any potential field, not just that due to gravity (Feynman et al. 1963, section 40-2). For example, we can envision some generic force field of magnitude \( F \) acting on each of the molecules in population \( n \) and directed along coordinate \( x \). We thus find a balance between the difference in pressure across a slab oriented perpendicular to \( x \) and the force per unit area acting on the slab. Assuming the ideal gas law at constant \( T \), and noting that \(-Fdx = dU\) is just the change in potential energy by virtue of the work done in moving the molecules through distance \( dx \) against the force, integration yields the result

\[
\frac{n}{n_0} = \exp \left( -\frac{U}{k_B T} \right). \tag{SB4}
\]

This equation, one form of Boltzmann’s law, states that at constant temperature the concentration \( n \) of molecules at elevated potential energy \( U \) is reduced over the concentration in the base state by the Boltzmann factor, \( \exp \left( -U/k_B T \right) \). This expression lies at the foundation of the atomistic view of physics (statistical mechanics).

We thus gain a compelling perspective for interpreting vapor pressure resulting from the integrated Clausius–Clapeyron equation [Eq. (SB2)]. Expressing Eq. (SB2) in molecular terms, we see that the pressure ratio becomes

\[
\frac{p}{p_0} = A \exp \left( \frac{-L_v}{RT} \right), \tag{SB5}
\]

where \( L_v \) is the latent heat per molecule. We can interpret the latent heat \( L_v \) as the potential energy of molecules in the vapor phase relative to those in the liquid. We have emphasized the common roots of Eqs. (SB3) and (SB5) but should also recognize that we typically consider variations in \( z \) (in the numerator) for hydrostatic balance and variations in \( T \) (in the denominator) for vapor pressure; thus, vapor pressure \( p \) must vary in the opposite sense that molecular concentration \( n \) does in the atmosphere, as the independent variable changes.

**Fig. SB1.** The dependence of the equilibrium vapor pressure ratio of water on temperature, as calculated from the Magnus equation (Pruppacher and Klett 1997, p. 854).
\[
\frac{n(T)}{n(T_0)} = T \exp \left( \frac{L_n}{k_B T} \right)
\]

when the ideal gas law is used to convert pressure into concentration. (The factor \(T/T_0\), arising from the expansion of the real vapor with temperature, can be ignored here.)

**MECHANICAL SYSTEM, DATA COLLECTION, AND ANALYSIS.** The fundamental concept behind this demonstration, replacement of the mean electrostatic binding potential in a real liquid by a gravitational potential energy well, is realized by milling a depression into the center of a flat aluminum disk (refer again to Fig. 2). Small spherical balls of copper or aluminum, the analogs of molecules, were able to bounce and migrate anywhere within the confines of the outer wall in response to the plate vibrations. Particles (balls in the mechanical system or molecules in a real liquid) naturally seek the lowest gravitational potential energy in the absence of other forces, but they may be ejected from the potential well if they happen to acquire sufficient kinetic energy (from the plate or from neighboring particles). The circular symmetry of the mechanical system (Fig. 2, bottom) offers the perspective, when viewed from above, similar to that of a drop of water in air.

The mechanical system was devised with a few considerations in mind. The plate (15 cm in diameter) was constructed of aluminum (6 mm thick) to minimize its mass and provide a hard, robust surface upon which the metal balls could bounce readily. Also, the rigidity of the plate served to prevent unwanted mechanical resonances. It was found that machining the surface with a very gentle slope (\(-1/4^\circ\)) toward the center helped compensate for the friction that naturally arises in a mechanical system. The central depression (2.5 cm in diameter) was cut 3 mm deep and placed in the center of the disk, mainly for symmetry. The outer wall was constructed of parchment paper and attached to the outer edge of the plate to keep the balls confined to the plate. The entire plate was spray-painted black to give visual contrast to the shiny balls. The bottom of the aluminum disk was outfitted with an adapter that permitted attachment to a mechanical wave generator, the frequency and amplitude of which were driven by a function generator. Further details on constructing the apparatus are provided in the online supplement (http://dx.doi.org/10.1175/BAMS-D-15-00173.2).

The amplitude of plate oscillations, needed to estimate the kinetic energy imposed on the particles, was determined optically. As illustrated in Fig. 2 (top), a (green) light from a laser pointer was focused and made to reflect first off a plane mirror attached to the bottom of the vibrating plate, then off a spherical mirror (focal length \(-20\) cm) that was mounted near the opposite side of the plate. This technique allowed the variations in the light path arising from the small (<1 mm) vertical excursions of the plate to be greatly amplified (~240 times) when projected onto the room wall about 6 m from the apparatus. A set of calibration experiments was performed in which the peak-to-peak range of the projected light was measured for each voltage setting of the function generator. The resulting regression equation was used, in conjunction with the measured magnification factor, to calculate the amplitude \(A\) of the plate oscillations from the measured voltages with a precision of a few percent for each experiment.

Data of particle “evaporation” were gathered from video records of the vibrating plate with bouncing balls. The digital video camera that generated these records was mounted above the plate and yielded many complete images (as in Fig. 2, bottom) for a period of 3 min at each amplitude. The stored images were later played back and stopped every 5 s, yielding 37 frames for data collection. This time interval was chosen as a compromise between the needs for the separate realizations of the particle distributions to be independent and for the number of samples (determinations) to be statistically meaningful. A relatively few (~60) large (2.4-mm diameter) copper balls work well for demonstration purposes, but the data here were gathered using a greater number (300) of small balls.

![Fig. 1. An alternative way of showing the dependence of the equilibrium vapor pressure ratio of water on temperature: Arrhenius plot of the vapor pressure normalized to the ice point \(T_0 = 273.15\) K (at which \(p_0 = 611\) Pa).](image-url)
(0.79-mm diameter) aluminum balls (McMaster-Carr) to improve statistics. The data from each voltage setting (yielding amplitude category $k$) of the mechanical vibrator are expressed as the average number $N_k$ of balls observed to be out of the well (i.e., “evaporated” and on level 2), from which a normalized ratio was calculated:

$$r_k = \frac{(N_2/N_1)_k}{(N_2/N_1)_0}.$$  

An “uncertainty” $\delta N_k$ about the mean, taken as the standard deviation, was propagated to the overall uncertainty in $r_k$ by standard methods (e.g., Taylor 1997), as outlined in the online supplement.

The mean kinetic energy $E_{\text{kin}}$ imparted to the balls on the plate by the mechanical vibrator served as the analog of the thermal energy $k_BT$ that drives the motions of molecules in a real liquid–vapor system. Determining the mechanical kinetic energy is challenging, in part because no convenient “thermometer” is available and because some of the mechanical energy is quickly dissipated by friction, something that does not exist as such in the molecular world. However, our purposes here are served adequately by assuming that the energy used for analysis of the data are linearly related to the hypothetical “true” energy imparted to the balls. We therefore use the square of maximum plate speed for the “relative energy” $E_{\text{rel}} = (A\omega)^2 \propto E_{\text{kin}}$, where $A$ is the amplitude of plate motion (as described above) and $\omega = 2\pi f$ is the angular frequency of the applied voltage.

**RESULTS AND DISCUSSION.**

The results presented here were derived from a series of nine experiments using the $N_{\text{tot}} = 300$ aluminum balls. The conditions and experimental results are summarized in Table ES1 in the online supplement. The number ratio $N_2/N_1$ (where $N_1 = N_{\text{tot}} - N_2$) for each amplitude category $k$ is shown in Fig. 3 (top) plotted against the relative energy $E_{\text{rel}}$ of the plate. One clearly sees the qualitative trend that the balls “evaporate” and jump from the lower level (the potential energy well) to the upper level more readily as the imposed energy (the “temperature”) increases. Low energies permit only a tiny fraction of the balls in the well to gain the requisite energy needed for promotion to the higher level; large energies, by contrast, let many of the balls escape the well. To first approximation, the balls mimic the quasi-exponential pattern from the evaporation of water (Fig. 1) as the temperature increases.

The data from balls jumping out of a potential well in this mechanical
system can be interpreted further with the help of Boltzmann statistics. An underlying feature of classical statistical mechanics is the fact that all energy states are equally likely, so a closed system overall tends toward the most probable distribution. If the balls in our mechanical analogy interact with the plate and with each other in random and independent ways, then the form of the dependence of the relative number densities in the upper and lower states should depend on the mean kinetic energy in the same way it does for the evaporation of true liquids [Eq. (3)]. We have put our data into an analogous form [Eq. (2)] by normalizing the number densities to a particular value \( N_{20} \) from amplitude category \( k = 9 \) and then plotting the normalized ratio [Eq. (4)] against the reciprocal of the relative energy. We see (by comparing the bottom panel of Fig. 3 with Fig. 1) that the overall pattern exhibited by the data from the mechanical analogy is, to good approximation, linear in semilogarithmic coordinates, just as it is with true molecular evaporation. It surprised us to find that such a few short segments of data from a system containing a mere 300 particles can be so well described by Boltzmann statistics.

The scatter in the data, too, provides insight into the statistics of balls bouncing on a plate. The “error” bars shown in Fig. 3 (bottom) are everywhere large compared with the standard errors of the means (white boxes), which shows the distinction that must be made between the fluctuations inherent in any statistical system and the ability to approach physically meaningful expectation values (the means) by repetitive sampling. The individual determinations (of \( r_k \) from the counting of balls on the upper level of the plate) will always vary greatly when the numbers are small. Nevertheless, we see from Fig. 3 (bottom) that the standard deviations (indicated by the error bars) follow the boundaries (shaded region) described by Poisson statistics quite well. Increasing the number of determinations will improve the estimation of the mean but not the statistical fluctuations. The only way to beat down that statistical uncertainty is to increase the number of particles in the system. Using more balls in the vibrating-plate experiment would help here; real liquid–vapor systems do this naturally because of the huge numbers of molecules involved. (Note that uncertainties in vapor pressure data arise from imprecision in the instruments making the measurements and not from the type of statistical uncertainties discussed here.)

Several caveats need to be stated about our physical system. The regular sinusoidal motion imposed on the plate by the mechanical actuator is not all similar to the random way in which thermal energy is transferred to or from a temperature bath. Moreover, most of the particle motions arise from interactions with the plate itself and not with other particles. The fact that this mechanical system obeys Boltzmann statistics so well may arise from the chaotic nature of particle–particle collisions and even of particle–plate interactions when many impacts occur per second.

**Fig. 3.** Data from the vibrating plate using a total of \( N_{30} = 300 \) aluminum balls. (top) Count ratio vs relative energy applied to the vibrating plate. Here \( N_u \) is the number in the upper level and \( N_w = N_{30} - N_u \) is the number in the well. (bottom) Arrhenius plot of the concentration ratios normalized to the maximum degree of “vaporization” from the vibrating-plate experiment. The filled circles represent the mean values of the normalized ratio from 37 trials at each energy level, while the white boxes represent the standard error of the means. The solid line is the best fit to the mean values and accounts for 99.5% of the variance. The error bars indicate the plus and minus standard deviations about the means. The shaded region identifies the theoretical range of uncertainty arising from a system obeying Poisson statistics.
SUMMARY. The mechanical analogy of balls on a vibrating plate containing a depression serves a couple of useful purposes. The mechanical system has a behavior predicted by Boltzmann statistics and therefore also illustrates the essential physics of the Clausius–Clapeyron equation. The mere existence of a potential energy well in a system of agitated particles is sufficient to guarantee that the equilibrium “vapor” density increase with “temperature,” a measure of the energy imposed on the particles comprising the system. Escape of molecules from the “liquid” phase is simply a matter of probability; those lucky few with kinetic energy exceeding the energy depth of the potential well are likely to escape; otherwise, they remain trapped in the well. Finally, the coupling of theory (thermodynamics and statistical mechanics) with data from a macroscopic system yields valuable information about the particle-scale and thermodynamic properties of the system. Vapor pressure above a liquid increases with temperature simply by virtue of the cohesive forces holding molecules in the liquid. It is one of the beauties of science that a molecular phenomenon like the probability of escape from a binding energy in a liquid can have global consequences: the physics of balls bouncing out of a depression in a vibrating plate or of molecules escaping from a liquid underlies the “water vapor feedback,” the increase of water vapor concentration in the atmosphere as global-mean temperature increases, and the concomitant enhancement of the greenhouse effect.

For teachers, we envision that the system described here can be useful as a classroom demonstration in an atmospheric thermodynamics course or similar. To further that end, we have made an animation of the mechanical demonstration, which is available online (http://phy.mtu.edu/vpt/). Moving the slider along the temperature scale in the animation shows how adding energy to the system increases the likelihood of particles escaping the central potential well. Or the system can be reproduced without great expense or effort to serve as part of an undergraduate atmospheric physics laboratory. We find the quantitative illustration of Boltzmann statistics to be highly instructive, and the analysis also serves to teach several useful concepts in error analysis. It is our hope that this demonstration serves to enlighten all of us students about the inner workings of liquid–vapor interactions.

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REFERENCES


Typhoon-induced rainfall remains one of the most important and challenging issues for both research and forecast operations. In particular, accurate representation of the extreme rainfall is very important for disaster prevention since serious flooding events are generally associated with heavy or extreme rainfall. Taking the typhoon impact in Taiwan as an example, multiple factors can affect the rainfall amount and distribution and give rise to considerable uncertainty in quantitative forecasts of typhoon-induced precipitation (Wu and Kuo 1999). It has been suggested that factors influencing the typhoon-related rainfall in Taiwan include the topographic effect of the Central Mountain Range (e.g., Chang et al. 1993; Wu et al. 2002; Tsai and Lee 2009); interaction between typhoon circulation patterns and the Asian monsoon system, such as the northeasterly winds late in the typhoon season and southwesterly winds in the summer (Wu et al. 2009; Yu and Cheng 2014); impacts from other nearby typhoons (Wu et al. 2010a); and the locations of the typhoons relative to the topography of Taiwan (Wu et al. 2013).

Occasionally, such interactions among the multiple factors above could cause extremely heavy rainfall events. For instance, Typhoon Morakot (2009) lashed southern Taiwan, bringing torrential rainfall, peaking at...
3000 mm in 4 days, that resulted in catastrophic floods and landslides. A number of studies have addressed the physical reasons behind the Morakot-produced heavy rainfall from different scientific perspectives, such as the large-scale moisture convergence, the confluent flow due to interactions between the typhoon’s outer circulation pattern and the concurrent southwesterly monsoon, the asymmetric typhoon structure, the slow translation speed, oceanic conditions conducive for typhoon development, and the impact of Typhoon Goni (Ge et al. 2010; Hsu et al. 2010; Wang et al. 2010; Wu et al. 2010b; Yeh et al. 2010; Zhang et al. 2010; Yen et al. 2011; Jou et al. 2012; Wang et al. 2012; Yu and Cheng 2013; Wu 2013). Wu and Yang (2011) coordinated a special issue of the journal Terrestrial, Atmospheric and Oceanic Sciences (TAO) entitled, “Typhoon Morakot (2009): Observation, Modeling, and Forecasting Applications,” which specifically focused on analyses of the different processes discussed above.

In addition to the investigation of a single extreme rainfall case, the long-term characteristics of the typhoon-induced rainfall and their connection to climate change or global warming is another important research topic (Liu et al. 2009; Chang et al. 2013). Chang et al. (2013) used rainfall data from 21 conventional weather stations operated by the Central Weather Bureau (CWB) in Taiwan to examine the rainfall statistics for typhoons that made landfall in Taiwan from 1960 to 2011. They reported that 8 of the top 12 typhoons in terms of total rainfall occurred after 2004. Nevertheless, most conventional stations are distributed along the coast with only three stations (i.e., station numbers 9–11, marked in Fig. 1a) located in the mountainous areas (above 1000 m) of central Taiwan. None of the conventional stations were deployed over the mountainous regions in northern and southern Taiwan, where very intense rainfall has been frequently observed as typhoons.

**Fig. 1.** (a) Locations of the 21 CWB conventional weather stations. Locations of the conventional weather stations (black squares) and automatic rain gauge stations (cross marks) in operation during (b) 1980, (c) 1990, (d) 1993, (e) 2000, and (f) 2013 with conventional stations marked by squares. The total number of stations is shown in the bottom-left corner of each panel. The topography of Taiwan is shaded.
influence Taiwan (e.g., Yu and Cheng 2008; Yu and Cheng 2014). It is reasonable to presume that the analysis results based on the few conventional stations, which are unevenly distributed, are not adequately representative of the typhoon-induced rainfall in Taiwan.

To address this issue, this study attempts to 1) examine the impact of rainfall data that are recorded at the limited, unevenly distributed conventional stations on the statistical characteristics of the typhoon-associated rainfall near Taiwan, and 2) highlight the importance of using data from a large number of automatic rain gauge stations, which became available starting in the 1990s, to assess the statistical features of the typhoon-related rainfall.

This article is organized as below. The data and methodology are described in the next section, comparisons between the results from the conventional stations and all the available rain gauges are given in the results section, and the final section of the paper offers the concluding remarks.

**Fig. 3.** The average accumulated rainfall amount per station (mm) for a single station calculated based on data from Con-ST (black) and from All-ST (red) for all 53 typhoons. Fitting lines are shown based on data from Con-ST, All-ST, and the top 10% rain gauge stations of Con-ST and All-ST (in terms of respective total rainfall for all 53 typhoons). Names of the top 10 highest ranking typhoons in terms of average rainfall amount based on All-ST are also labeled.
Figure 1 shows the locations of the 21 conventional weather stations and the automatic rain gauge measurements from the CWB during some representative years. It is clear that the number of automatic rain gauges has significantly increased since 1990, while the number of rain gauges located below the altitude of 500 m has always accounted for more than 70% of all stations (Fig. 2). In other words, the percentage of the stations located above 500 m has been higher than 20%, but never reached 30%, and those located above 1000 m have accounted for around 10%–15% of the total. Stations at higher elevations (above 2000 or 3000 m) cover even smaller percentages.

Hourly rain gauge data from the conventional weather stations and the automatic rainfall gauges are used to obtain statistics related to precipitation induced by typhoons that have struck Taiwan between 1993 and 2013. In this study, the total accumulated rainfall for each typhoon is obtained during a time period when the typhoon center is within a distance of 100 km from the nearest coastline, similar to the definition in Chang et al. (2013). In addition, an index of the average rainfall amount for a single station during the typhoon's influence is calculated by summing the total accumulated rainfall from all the available rain gauges and dividing it by the number of gauge stations. For convenience, the selected 21

<table>
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<th>Impact time in Taiwan</th>
<th>Type of track</th>
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<td>X</td>
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<td>Other</td>
</tr>
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<td>29</td>
<td>Nanmadol (2004)</td>
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<td>2000 UTC 3 Dec</td>
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conventional weather stations [basically those used in the analysis of Chang et al. (2013)] are referred to as Con-ST, while all rain gauge stations (including both the conventional and automatic gauge stations) are referred to as All-ST.

RESULTS. Fifty-three typhoons struck Taiwan from 1993 to 2013. Among the 12 typhoons with the highest average rainfall amount based on Con-ST data (21 stations; Fig. 1a), 4 occurred before 2004 [Typhoons Herb (1996), Zeb (1998), Xangsane (2000), and Nari (2001)] and the remaining 8 typhoons occurred after 2004, consistent with the results in Chang et al. (2013) based on typhoons from 1960 to 2011. However, if the reference is expanded to include all data from All-ST (about 250–500 stations; Fig. 1), the number of typhoons before 2004 drops to three, yet with a slightly different composition [Typhoons Herb (1996), Toraji (2001), and Nari (2001); Table 1] compared to Con-ST.

![Table 1. Continued.](image)

<table>
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<tr>
<th>No.</th>
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<td>14</td>
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a Starting time is defined as when the typhoon center moves to a location that is within 100 km to the nearest coastline of Taiwan.

b Ending time is defined as when the typhoon center departs for a location that is 100 km away from the nearest coastline of Taiwan.

X indicates storm did not make landfall in Taiwan.
both dashed lines show similar increasing temporal trends, each line has a rather weak linear-regression correlation. The number of typhoon cases with average rainfall exceeding 150 mm appears to be higher after 2004 as compared to those before 2004, as indicated in Chang et al. (2013). For each typhoon case, the mean value of the average rainfall for a single station based on the All-ST data is larger than that based on the Con-ST by about 8 mm.

To further examine the above observations, we divide the data into two 10-yr groups: Data-1 for 1994–2003 and Data-2 for 2004–13. Table 2 shows $t$-test results (Larsen and Marx 1981) for the comparison of Data-1 and Data-2 between Con-ST and All-ST. First, it is found that the $p$ value for the comparison of Data-1 and Data-2 from All-ST is less than 0.05. Therefore, a significant difference (at a confidence level of 95%) can be identified between Data-1 and Data-2 for All-ST, while the difference between Data-1 and Data-2 for Con-ST does not pass the significance test (at the 90% confidence level). The above result again highlights the importance of using All-ST data. We also calculate the $p$ value of the average accumulated rainfall from stations with the top 10%, 15%, 25%, 50%, and 100% rainfall for Con-ST and All-ST (Table 3). It is found that the $p$ value is less than 0.05 for the comparison of the top 10% and 15% groups, indicating a significant difference in average hourly rainfall per station between the top 10% and 15% of both Con-ST and All-ST. This analysis shows that although the average rainfall amount calculated from Con-ST is similar to that from All-ST, Con-ST cannot identify the precipitation extremes (such as the top 10% and 15% rainfall amounts). Hereafter, further analysis based on stations with the top 10% rainfall is conducted to show more statistics related to extreme rainfall.

The top 10% rain gauge stations for the top 10 highest ranking typhoons (hereafter referred to as top 10 typhoons, with each name indicated in both Figs. 3 and 4) in terms of average rainfall amount based on All-ST data are mostly distributed across the mountainous areas of above 1000-m altitude, where only 3 of the 21 conventional stations (Con-ST) are located (cf. Figs. 1 and 4). In addition, most of the top 10 typhoons passed over northern Taiwan (Figs. 4a,c,d,e,f,g,i,j). The relationship between the average accumulated rainfall per station calculated based on All-ST with respect to the duration of each typhoon’s influence over Taiwan is displayed in Fig. 5. The positive correlation between the average rainfall and duration is more evident in the assessment for the top 10 typhoons (black), with a correlation coefficient ($R$) of 0.77. Meanwhile, the

| Table 2. The $t$ tests for Data-1 and Data-2 of Con-ST and All-ST with $t$ values and $p$ values for comparison. Data-1 and Data-2 are two 10-yr groups ranging between 1994 and 2003 and 2004 and 2013, respectively. |
|------------------|------------------|------------------|------------------|
| $t$ test         | Avg accumulated | Avg accumulated | Avg accumulated |
|                  | rainfall per     | rainfall per     | rainfall per     |
|                  | station between  | station between  | station between  |
|                  | Data-1 and Data-2| Data-1 and Data-2| Data-1 and Data-2|
| Data-1 (mm)      | 93.7             | 93.0             |
| Data-2 (mm)      | 122.5            | 138.8            |
| $t$ value        | 1.6198           | 2.3320           |
| $p$ value        | 0.1256           | 0.0475           |

| Table 3. The $t$ and $p$ values from $t$ tests of average accumulated rainfall from the stations with the top 10%, 15%, 25%, 50%, and 100% of rainfall from Con-ST and All-ST. |
|------------------|------------------|------------------|------------------|
| $t$ test         | Avg accumulated | Avg accumulated | Avg accumulated |
|                  | rainfall per     | rainfall per     | rainfall per     |
|                  | station from the | station from the | station from the |
|                  | top 10% of Con-ST| top 15% of Con-ST| top 25% of Con-ST|
|                  | and All-ST       | and All-ST       | and All-ST       |
| Con-ST (mm)      | 238.6            | 242.0            | 229.3            | 178.0            | 109.5            |
| All-ST (mm)      | 341.0            | 317.3            | 261.4            | 193.2            | 118.1            |
| $t$ value        | 2.7893           | 2.2911           | 1.1019           | 0.6812           | 0.6327           |
| $p$ value        | 0.0140           | 0.0405           | 0.2023           | 0.3068           | 0.3205           |
Fig. 4. The distribution of the accumulated rainfall during the typhoons' influence over Taiwan. Only the top 10 typhoons are shown. Locations of the top 10% rain gauge stations in terms of total rainfall amount are marked by crosses, among which the conventional stations are indicated by squares. The best track analyzed by the CWB is shown by typhoon symbols every 3 h. The letters S and E indicate the typhoon positions when the typhoon center approaches to within 100 km of the nearest coastline and at its departure time when the typhoon center is 100 km away from the nearest coastline, respectively. The thick black contour indicates the terrain above 500 m.
The correlation coefficient between the average rainfall and the duration time for all 53 typhoons slightly decreases to about 0.67. However, the correlation coefficient drops to 0.28 when the data from the top 10 typhoons are excluded, suggesting that a strong correlation between the average rainfall and the impact duration of a typhoon mainly exists for typhoons with the most pronounced rainfall.

To further understand the statistical difference between the Con-ST and the All-ST results in the mountainous areas, the ratio of rainfall over the mountainous areas to the total rainfall amount is examined. The mean ratios calculated from Con-ST above 3000, 2000, and 1000 m and averaged for all typhoon cases are 8.2%, 18.6%, and 23.7%, respectively (Fig. 6a), while the mean ratios from the All-ST results are strongly reduced to 0.9%, 3.0%, and 9.1% (Fig. 6b). Note that only one (Yushan station) out of the 21 conventional stations is located above an elevation of 3000 m and only another one (Alishan station) is located between the elevations of 2000 and 3000 m.

**Fig. 5.** The average accumulated rainfall amount per station (mm) based on data from All-ST vs the duration for all 53 typhoons (red circles), the top 10 typhoons (black squares), and all typhoons excluding the top 10 typhoons (blue circles) during their time impacting Taiwan. The corresponding linear fitting line and equation are also shown.

**Fig. 6.** The percentage of rainfall measured by Con-ST and All-ST above (a) 3000, (b) 2000, and (c) 1000 m, with respect to the total rainfall during each of the 53 typhoons.
Fig. 7. The typhoon best tracks analyzed by the CWB for (a) N-, (b) C-, and (c) S-type typhoons. Typhoon tracks indicated start where the typhoon center is within 100 km of the nearest coastline (indicated by purple numbers) when approaching Taiwan and ends where the typhoon center is 100 km away from the nearest coastline (indicated by the black numbers) when departing Taiwan. Table to the bottom right shows the analyzed typhoons with their case numbers.

Fig. 8. The average hourly rainfall amount per station (mm h$^{-1}$) based on data from All-ST and solely on Con-ST located in the four zones of Taiwan, averaged by groups of N-, C-, and S-type typhoons, respectively.

It has been shown that the location of Alishan station is close to one of the heavy precipitation centers during typhoon rainfall events (Wu et al. 2002; Yu and Cheng 2014). Therefore, the percentage of rainfall at higher elevations is most likely overestimated if only the three conventional stations in the mountains are considered, because of their quite limited numbers and their uneven distribution over the mountainous areas. This result suggests that the statistical analyses conducted solely based on Con-ST are unable to represent the partitioning by terrain heights of the rainfall associated with typhoons in Taiwan.

To understand the statistical rainfall features in relation to typhoon tracks, we categorize the landfalling typhoons into three types based on their landfall locations [as in Chang et al. (2013)], namely, around northern Taiwan (N type, landfalling to the north of 23.6°N), across central Taiwan (C type, landfalling between 23.1° and 23.6°N), and over southern Taiwan (S type, landfalling to the south of 23.1°N) (Fig. 7). Figure 8 shows the average hourly rainfall per station of the three track types of typhoons based on the rain gauge data in four different zones.
of Taiwan. In northern, central, and southern Taiwan, the N-type typhoons produce the largest average hourly rainfall in each portion of Taiwan as compared to those in the other two track types. In particular, the largest average hourly rainfall produced by the N-type typhoons occurs across both central and southern Taiwan, which is more than the hourly rainfall in northern Taiwan, where the storm centers pass by (Fig. 7a). This result is consistent with previous findings (Wu and Kuo 1999) that the cyclonic circulation of the typhoons can interact with the low-level southwesterly flow to strengthen the confluence flow while the convection is further enhanced along the upslope side of the Central Mountain Range of Taiwan, thus leading to the heavy rainfall in central and southern Taiwan. Meanwhile, the smallest average hourly rainfall occurs in eastern Taiwan for the N-type typhoons since it is located to the lee side of the Central Mountain Range as the storm centers pass over northern Taiwan (Wu et al. 2002). As with the results obtained from All-ST, the largest average hourly rainfall of Con-ST produced by the N-type typhoons occurs in central Taiwan with a value of 12.53 mm h⁻¹ (Fig. 8). Figure 8 demonstrates that the average rainfall results from Con-ST offer a clear positive bias as compared to the All-ST results in central Taiwan. This is in part due to the fact that the three mountainous rain gauges in Con-ST above 1000-m elevation are all located in central Taiwan (cf. Figs. 1a and 4), thus leading to much higher average hourly rainfall result compared to Con-ST.

To understand the difference in the percentage of stations that measure the rainfall above certain criteria between Con-ST and All-ST, the cumulative frequency (Wu et al. 2002, 2013) of the average hourly rainfall is examined and compared among the three track types (Fig. 9). One common robust feature among the different track types is that the cumulative frequency assessed by data from stations at elevations below 500 m (black lines) is closer to that from stations at all elevations (red lines), while the cumulative frequency assessed by the data from stations above 500 m (mountainous areas) deviates from it. For stations located above 500 m, the cumulative frequency based on

![Figure 9](image-url)
the Con-ST dataset is generally higher than that associated with All-ST for the N and C storm types, as well as for all 53 typhoons. In contrast, a higher percentage of the Con-ST data measure the average hourly rainfall below 4 mm h$^{-1}$, while a smaller percentage of the Con-ST data measure hourly rainfall between 4 and 10 mm h$^{-1}$ (green lines in Fig. 9c). With only 4 conventional stations (out of the total of 21) located above 500 m, the cumulative frequency from the Con-ST dataset in the mountainous areas is likely less representative and biased toward larger rainfall amounts in the N and C types, while stronger (lighter) rainfall events of S type are underestimated (overestimated). Furthermore, from both Con-ST and All-ST the cumulative frequency calculated with data from stations above 500 m is evidently higher in both N and C types as compared to that below 500 m (i.e., the green lines are located well above the red and black lines in Figs. 9a–c). In other words, precipitation induced by typhoons that pass over northern and central Taiwan mostly occurs at higher elevations. This statistical characteristic highlights the importance of topographically forced vertical motions in intensifying rainfall as the N- and C-type typhoons bring strong westerly and/or southwesterly flow that impinges on the mountainous regions of central and southern Taiwan (Wu et al. 2002; Yu and Cheng 2013; Yu and Cheng 2014).

The extreme rainfall amount is shown in Fig. 10 as the accumulated rainfall calculated based on the highest 10% of the accumulated rainfalls during the typhoons. Such extreme rainfall results are underestimated, on average, by 23.3%, 43.5%, and 37.2% in N-, C-, and S-type storms, respectively (Table 4), when only the Con-ST data are used [with only a few exceptions, such as Gladys (1994) and Herb (1996) being the N type, and Wutip (2007) being the C type]. The most significant underestimation occurs in the C type, in which typhoons make landfall in central Taiwan, again implying the critical impact of topography on the extreme rainfall amounts. The added value of the All-ST data in assessing the long-term characteristics or the change in the extreme rainfall amount and the rainfall distribution associated with typhoons and the complicated Taiwan topography are therefore worth noting.

**SUMMARY.** The statistical characteristics of rainfall associated with 53 typhoons from 1993 to 2013 are examined based on the rainfall data from all of the available automatic rain gauges (All-ST) and conventional weather stations (Con-ST) from the CWB of Taiwan. Analyses from both kinds of data indicate a statistically insignificant but slightly increasing trend in the average rainfall amount produced by typhoons during the 21 years of study. In addition, a strong correlation between the average rainfall and the impact duration of a typhoon exists mainly for typhoons with the most pronounced rainfall based on All-ST data. The top 10 typhoons in terms of average rainfall amount from the All-ST dataset are found to pass over northern Taiwan,
which leads to larger rainfall over the mountainous regions of central and southwestern Taiwan.

Although the average rainfall amount assessed by Con-ST is statistically similar to that evaluated by data from All-ST, the rainfall data of the Con-ST cannot accurately capture the main features of both precipitation extremes and the rainfall distribution, especially for the mountainous areas. The uneven distribution and very sparse numbers of Con-ST stations over the mountainous regions (only three stations are located above an elevation of 1000 m) are likely to cause such biases in the interpretation of rainfall patterns at higher elevations where major typhoon-induced extreme rainfall tends to occur. Under such circumstance, the rainfall measured by Con-ST over the mountains is relatively overestimated, and the cumulative frequency calculated is less representative. Accordingly, analyses of statistical rainfall features solely based on the Con-ST dataset, as adopted in some previous studies, may be at risk of bias to a certain degree in depicting the long-term statistical characteristics.

The top 10% rain gauge stations for the top 10 typhoons in terms of average rainfall amounts based on the All-ST data are mostly distributed over the mountainous areas. In addition, the cumulative frequency for rain gauge stations above 500 m is higher than that for rain gauge stations below 500 m, indicating the important role of topography in affecting the rainfall distribution and amount. In all, this study highlights the value of the use of the high-density rain gauge data, especially over the mountainous areas, in identifying representative statistics of the typhoon-induced rainfall in Taiwan.

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REFERENCES


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Science at Your Fingertips
The coastal waters of the Northeast United States are an ideal location for developing offshore wind power given the combination of large wind resource, high population density, and shallow coastal bathymetry (Kempton et al. 2007; Dvorak et al. 2012b). Archer et al. (2014) identified three main areas of opportunity for facilitating offshore wind farm development through better meteorological observations and atmospheric modeling: 1) enhancing offshore wind resource assessment, 2) improving wind power forecasting, and 3) characterizing turbulent wake losses of wind farms. There are other challenges to developing offshore wind power, such as design of support structures, transmission, and interconnection to the power system; the trade-off between locating farther from shore to reduce visual impact and increase wind speed versus locating closer to shore for lower construction cost; environmental assessment; and financing, power purchase contracts, infrastructure, and supply chain development to reduce cost of electricity, among others. However, while relevant, they are not the subjects of this article.

There have been several wind resource assessments along the Northeast U.S. coastal waters (Manwell et al. 2002; Musial and Ram 2010; Dvorak et al. 2012a; Woods et al. 2013; Monaldo et al. 2014). Wind resource assessment in coastal and offshore areas currently suffers from a lack of observations at turbine hub height (i.e., around 100 m above mean water level); thus, the need for more multilevel observations...
of wind and temperature on offshore platforms was identified (Archer et al. 2014). Improved understanding and realistic modeling of coastal processes are also necessary for accurate wind resource assessment and wind forecasting, yet current numerical weather prediction models and their parameterizations of the planetary boundary layer (PBL) have not been comprehensively evaluated in this offshore area. Since the power available in the wind is proportional to the cube of wind speed, small wind speed forecast errors can result in large errors in the prediction of the available power. Accurate representation of mesoscale and synoptic-scale processes is important for resource assessment and return on investment planning prior to construction as well as to operational forecasts such as hour-ahead and day-ahead power production forecasts, upon which unit commitment and scheduling decisions are based.

There are important diurnal circulations near the Northeast coast during the warm season, such as sea breezes (Hughes and Veron 2015; Novak and Colle 2006; Colby 2004) and low-level jets (LLJs). Colle and Novak (2010) showed the existence of a diurnally forced LLJ in the New York Bight region that often consisted of winds with speeds in excess of 13 m s\(^{-1}\). Other LLJs have been documented along the U.S. East Coast associated the sloping Appalachians and coastal temperature boundaries along the mid-Atlantic during the warm season (Zhang et al. 2006; Ryan 2004) and low-level temperature boundaries near the coast during the cool season (Doyle and Warner 1991). Occurrences of the New York Bight jet peak on days in the late springtime when the land–sea temperature contrast is the greatest and when the flow is primarily southwesterly around a Bermuda high pressure system. The southerly LLJs over the southern Great Plains develop under similar synoptic conditions (Bonner 1968), with surface high pressure situated to the east of the plains. The New York Bight jet maxima were found to occur at about 150 m above mean sea level (MSL), just above hub height of a typical offshore wind turbine, and were part of a larger-scale coastal wind enhancement in the southern New England region. Helmis et al. (2013) also confirmed the presence of several summertime LLJ structures above Nantucket, Massachusetts, using various observational datasets.

![Fig. 1. (a) Map of the IMPOWR observations used in the region. Photos of (b) the Cape Wind tower [green star in (a)], (c) Long-EZ aircraft that was deployed from near Westhampton Beach (FOK) on Long Island, and (d) a spiral of the Long-EZ over the Cape Wind tower. Photos credits: Dana Veron for (b), John Mak for (c), and Matthew Sienkiewicz for (d).]
Fig. 2. Examples of data collected around the Cape Wind tower showing the (a) average wind speed (m s\(^{-1}\)) at 20-, 41-, and 60-m levels at the tower during 2003–07, at 10 m from IMPOWR anemometers in 2013/14 on the tower platform, and at 5 m from nearby buoy 44020 during IMPOWR anemometers’ available times, with markers indicating one standard deviation, and (b) significant wave height (H\(\text{\textsubscript{s}}\) in meters) vs 10-m wind speed from the buoy and 10-m IMPOWR anemometer in 2013/14. The right shows the frequency of occurrence [probability density function (PDF)] of significant wave heights in \(dH\(\text{\textsubscript{s}}\) = 0.1 m bins. The significant wave height most frequently observed is approximately 0.4 m. The PDF is normalized such that \(\int (PDF) dH\(\text{\textsubscript{s}}\) = 1.\)
**MOTIVATION.** Mesoscale model verification efforts for offshore wind power across western Europe have used tall mast (~100 m), wind lidar, and satellite data. Carvalho et al. (2014a) and Hahmann et al. (2015) showed that Weather Research and Forecasting (WRF) Model surface winds are sensitive to the PBL and surface-layer parameterizations employed as well as to the reanalysis used. Even with these potential uncertainties, WRF-simulated wind data have been shown to be the best alternative to observed in situ offshore wind data (Carvalho et al. 2014b).

There has been limited verification of models near hub height (~100 m) over the coastal Northeast United States, given the scarcity of observations of the marine boundary layer in this marine environment. This region, stretching from the south shore of Long Island to Georges Bank, has been identified by Dvorak et al. (2012b) as an ideal location for an offshore wind energy grid based on available wind resource, regional energy demand, and shallow water depth. Previous studies have utilized available surface, sounding, and short-tower observations to validate WRF. Woods
et al. (2013) found relatively good agreement between the WRF and buoy observations over the outer continental shelf of the western Atlantic. Nunalee and Basu (2014) used a coastal radiosonde and profiler to show that the strength of an LLJ case in WRF near New York City was sensitive to the PBL parameterization and initial atmospheric conditions used but less sensitive to the sea surface temperatures and vertical model resolution. For extreme low wind speeds, the Coupled Boundary Layers Air–Sea Transfer (CBLAST; Edson et al. 2007) field experiment collected data around Nantucket island during the midsummer period during 2001–03 in order to improve models. The CBLAST observational tower extended to 24 m MSL, with additional turbulence, wind, and temperature data obtained by Long-EZ aircraft flights and SODAR.

The field campaign reported on here, Improving the Mapping and Prediction of Offshore Wind Resources (IMPOWR), addresses CBLAST deficiencies using data from a taller, 60-m tower as well as other observations within the PBL. The Cape Wind (CW) meteorological tower, located within Nantucket Sound (Fig. 1), was operational from 2003 to 2011 and recorded data at multiple levels (20, 41, and 60 m). A goal of IMPOWR is to collect observations to validate and improve the boundary layer parameterizations in models, especially during stable marine conditions.

The IMPOWR field program began in fall 2012 and continued through summer 2015, extending the analysis begun by CBLAST both geographically and seasonally. The goals of this paper are to provide an overview of the IMPOWR experiment and to describe a few case studies to further motivate the research. The cases illustrate a coastally enhanced flow event near Nantucket island and a New York Bight jet along the New Jersey coast.

**IMPOWR DESIGN. Observations.** A number of different in situ observational datasets were used during the IMPOWR experiment. Surface observations over the coastal waters were obtained from the National Data Buoy Center’s moored buoys and Coastal Marine Automated Network stations, while surface land observations were available from National Weather Service (NWS) Automated Surface Observing System stations (Fig. 1a). Except for the NWS radiosondes over eastern Long Island [Upton, NY (OKX)] and coastal Massachusetts [Chatham (CHH)], which provided 12-hourly observations of temperature, moisture, and winds throughout the PBL, all other datasets were at a single fixed height. Through a partnership with CW, historical data from the CW meteorological mast (Figs. 1b,d) were acquired, consisting of continuous 10-min observations of wind speed and direction at

<table>
<thead>
<tr>
<th>Flight day</th>
<th>Weather conditions</th>
</tr>
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<tbody>
<tr>
<td>12 Nov 2012</td>
<td>Cyclone warm sector with south winds</td>
</tr>
<tr>
<td>4 Apr 2013</td>
<td>Southwest flow around anticyclone</td>
</tr>
<tr>
<td>7 Apr 2013</td>
<td>Stable strong south flow ahead of warm front</td>
</tr>
<tr>
<td>9 Apr 2013</td>
<td>Southwest flow ahead of cold front</td>
</tr>
<tr>
<td>4 May 2013</td>
<td>Moderate northeast flow with a subsidence inversion at top of PBL</td>
</tr>
<tr>
<td>10 May 2013</td>
<td>Southwest flow with coastal sea breezes</td>
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<tr>
<td>16 May 2013</td>
<td>Southwest flow with coastal jet</td>
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<tr>
<td>20 Jun 2013</td>
<td>Coastal sea breeze with westerly flow aloft</td>
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<tr>
<td>21 Jun 2013</td>
<td>Coastal sea breeze with westerly flow aloft</td>
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<tr>
<td>23 Jun 2013</td>
<td>Southwesterly flow with coastal flow enhancement</td>
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<tr>
<td>24 Jun 2013</td>
<td>Weak New York Bight jet event</td>
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<tr>
<td>28 Sep 2013</td>
<td>Northeasterly flow around anticyclone</td>
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<tr>
<td>2 Oct 2013</td>
<td>Weak westerly flow</td>
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<tr>
<td>12 May 2014</td>
<td>Southwest flow with coastal jet</td>
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<tr>
<td>22 Jul 2014</td>
<td>New York Bight Jet</td>
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<td>23 Jul 2014 (flight 1)</td>
<td>New York Bight Jet (before jet)</td>
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<td>23 Jul 2014 (flight 2)</td>
<td>New York Bight Jet (after jet)</td>
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<tr>
<td>31 Jul 2014</td>
<td>Southwest flow with coastal jet</td>
</tr>
<tr>
<td>11 Nov 2014</td>
<td>Cold northwest flow over warmer coastal waters</td>
</tr>
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20, 41, and 60 m and temperature and pressure at 10 and 55 m above the sea surface over Nantucket Sound during 2003–11. As depicted in Fig. 2a, there is a strong seasonal cycle in wind speed at the CW tower, with the average winds gradually decreasing during the spring and early summer months, as diurnal circulations dominate synoptically driven systems, followed by a rapid increase of wind speed in October, as the synoptic pressure gradients increase. The winds at all three levels follow the same annual cycle, but the winds at 60 m are generally 10%–20% faster than at 20 m. Wind directions at the 20-m level of

**Fig. 4.** (a) Surface analysis over the Northeast United States and mid-Atlantic from the National Oceanic and Atmospheric Administration (NOAA) Weather Prediction Center at 1800 UTC 21 Jun 2013, with sea level pressure contoured every 4 hPa. (b) Wind speed from the Long-EZ flight track at 40–50 m [colored in knots (kt; 1 kt = 0.51 m s$^{-1}$) and each full barb is 5 m s$^{-1}$]. The box in (a) is the location of the flight level data in (a).
the CW tower have a strong seasonal signal too (Fig. 3), with southwesterly winds prevailing in the summer as a result of circulation around the offshore Bermuda high, while more frequent cold-air outbreaks from the North American continent result in more westerly to northwesterly winds during the winter.

At the start of the IMPOWR project, the CW instrumentation was no longer recording data, so the platform of the CW tower (~10 m MSL) was instrumented with wind, temperature, and relative humidity sensors at two locations, about 2 m above the platform; a high-speed optical wave gauge was also installed. The data were recorded continuously at 20 Hz and transmitted from the tower every 10 min. IMPOWR measurements were taken at the CW tower for about two years (April 2013–December 2014), although not continuously. Because of the limited power storage in the solar batteries, the system had to run on a 6-h reduced power cycle in the winter months; in addition, because of the loss of connectivity at the CW tower, no recording is available during July 2013 and 2014. The average wind speed from the IMPOWR sensors (Fig. 2a) shows very similar seasonal patterns to the historical data as well as to the nearby buoy 44020 (shown for the same sampling period as the IMPOWR data). The strong correlation between wave height and 10-m wind speed is also documented in Fig. 2b. Additional observations at 25 m MSL were available at the Buzzard’s Bay tower operated by the National Oceanic and Atmospheric Administration and at 24 m at the air–sea interaction tower (ASIT) that had also been used in the CBLAST experiment (ASIT in Fig. 1a). Finally, two lidars (from Deepwater Wind, LLC) were deployed in the summer of 2014 at Southampton on Long Island and at the southwest corner of Block Island to get continuous wind measurements from 18 to 150 m above the surface.

Aircraft flights were conducted as part of the IMPOWR field campaign during the spring and summer of 2013 and 2014. A Long-EZ aircraft was used during 2013 (Fig. 1c), while a Cozy Mark IV aircraft was used after the fall of 2014 (not shown). Both aircraft were fitted with the Aircraft Integrated Meteorological Measurement System (AIMMS-20) instrument, which is capable of recording observations of three-dimensional winds, temperature, pressure, and relative humidity at a frequency up to 40 Hz. Flight operations were based out of Brookhaven Airport (KHWV in Fig. 1a) and targeted the coastal areas of Nantucket Sound, Buzzard’s Bay, and Block Island Sound, as well as the New Jersey coast. Various flight maneuvers, such as constant-level flight legs, spiral soundings in the lowest 2 km, and slant-sounding flight legs below 1 km, were conducted in order to provide marine boundary layer profiles of momentum, thermal, and moisture fields, as well as turbulence and
flux quantities. A typical flight involved about an hour of transport to the location, around 2 h of sampling, and then the return flight to eastern Long Island.

**WRF setup.** The Advanced Research version of the WRF (ARW; Skamarock et al. 2008) Model, version 3.4.1, was used for a series of short-term (30 h) runs for two separate evaluation periods: the historical period centered on the available data from the Cape Wind Meteorological Mast (2003–11) and the IMPOWR aircraft flights conducted in 2013/14. This paper focuses on the simulations for the IMPOWR flights, in which a large 4-km domain was used as the outer domain over the Northeast United States, eastern Great Lakes, and Atlantic coastal waters, with a one-way, nested, inner 1.33-km domain (Fig. 1 region). The WRF Model employed the Yonsei University (YSU; Hong et al. 2006) PBL parameterization, unified Noah land surface scheme (Tewari et al. 2004), Rapid Radiative Transfer Model (RRTM) longwave radiation (Iacono et al. 2000), Dudhia shortwave radiation (Dudhia 1989), and Thompson microphysical parameterization (Thompson et al. 2004, 2008), with no convective scheme on either domain. The initial and lateral boundary conditions were supplied by hourly analyses of the National Centers for Environmental Prediction’s Rapid Refresh (RAP; Benjamin et al. 2009). The RAP was chosen for the WRF simulations of the flight cases because of its higher spatial and temporal resolutions, as well as improved data assimilation methods, relative to other available gridded analyses. The 1/12° daily gridded sea surface temperature (SST) product from the National Centers for Environmental Prediction was prescribed for all WRF runs. The model output interval for the 1.33-km domain was increased to 5 min in order to allow for interpolation of the model variables to the aircraft position in time and space.

**FIELD EXAMPLES.** As of early 2015, there have been 18 flights using the Long-EZ aircraft (Table 1). We sampled a variety of different flow regimes, with a focus on the diurnal coastal flows during the warm season. There were several southwesterly flow cases, with enhanced flows and jets near the coast, but also two offshore (westerly) or northeasterly flow events. All events had limited low cloud cover during the daytime (typically afternoon), which allowed more focus on the dry PBL processes during diurnal heating. Good visibility allowed the aircraft to descend to and sample 30–50 m above the sea surface.

Three example cases are discussed below to highlight the data collected as well as to show preliminary comparisons with the WRF Model. These events have enhanced southerly or southwesterly flow, with two events to the east of Long Island on 21 June 2013 and 31 July 2014 and a New York Bight jet event on 23 July 2014.

**21 June 2013 Nantucket event.** Three flights were conducted in the 4-day period of 20–23 June 2013, in the afternoons and evenings of 20, 21, and 23 June. The prevailing winds in the vicinity of Nantucket Sound during this period were predominantly south-southwesterly, with the presence of a high pressure center to the south and east (Fig. 4a), which increased in intensity throughout the period (not shown). By early afternoon (1800 UTC 21 June), the air temperatures increased to 28°–29°C over the interior of New England, while the air temperatures over the coastal waters measured by the buoys were 18°–19°C. As a result, the strongest southerly surface flow was 5–7 m s⁻¹ near the coast, while the winds were lighter and more variable over the interior land areas as well as farther offshore.

The Long-EZ aircraft took off at 1730 UTC 21 June and ferried to the

![Figure 6](image-url)
Nantucket area while remaining nearly parallel to eastern Long Island (Fig. 4b). It completed a series of short north–south stacks and a profile near the CW tower before returning back to Long Island following a similar track. Figure 4b shows the winds at about 50 m as the aircraft went toward Nantucket Sound.

Fig. 7. (a) Surface analysis over the Northeast United States and mid-Atlantic from the NOAA Weather Prediction Center at 2100 UTC 21 Jul 2014, with sea level pressure (contoured every 4 hPa). (b) The 1.33-km WRF wind speeds at 180 m (shaded; m s⁻¹; 1 full barb = 10 kt or ~5 m s⁻¹) at 2100 UTC 23 Jul (forecast hour 21).
There was a steady increase in wind speeds from 8 to 12 m s$^{-1}$ toward the east, which is suggestive of coastal enhanced low-level southerly flow. Figure 5a shows an analysis of the winds and potential temperatures for the north–south stacks into and out of Nantucket Sound and the spiral at CW. The observed static stability (vertical potential temperature gradient) is largest to the south and strongest around 150 m; this stable layer weakens and increases in height to the north. This is consistent with SST differences increasing from south to north, ranging from about 16$^\circ$C just south of Nantucket Sound to about 20$^\circ$C inside the sound (not shown). The observed marine layer in the observations is deeper over the northern half of the cross section, which hydrostatically enhances the surface pressure difference between these coastal water locations and the interior land areas, thus resulting in enhanced flow (11–13 m s$^{-1}$) compared with locations to the south.

The WRF simulation with the YSU PBL is compared with the aircraft observations 18–21 h into the forecast at 1.33-km grid spacing. At 1800 UTC (Fig. 6), the WRF Model diurnally warms the interior up to 28$^\circ$C at the surface; the surface winds are 5–8 m s$^{-1}$ near the coast (Fig. 4a), while only 2–3 m s$^{-1}$ south of Long Island, which is nearly 4 m s$^{-1}$ weaker than the buoy observations. For the north–south cross section (Fig. 5b), the WRF isentropes are relatively flat at low levels with no evidence of a well-defined marine layer, and as a result, the winds are 2–3 m s$^{-1}$ weaker than observed. The WRF Model does develop a more defined stable layer eventually by 2100 UTC (Fig. 5c), but the layer is very thin, extending from the surface to about 100 m, and the modeled winds are 1–2 m s$^{-1}$ weaker than the 1800 UTC observations over the center part of the cross section. Overall, the WRF Model developed the enhanced winds too slowly and the strongest winds are located too close to the coast.

23 July 2014 New York Bight jet event. Two flights occurred on 23 July 2014 to observe the development of the New York Bight jet along the New Jersey (NJ) coast toward western Long Island. At 1800 UTC 23 July, there was surface high pressure offshore of the U.S. East Coast (Fig. 7a), and there was a cold front over central New York (NY) and Pennsylvania that was progressing eastward. The surface temperatures ahead of this front around New York City (NYC) were 32$^\circ$–33$^\circ$C, while they were 24$^\circ$–25$^\circ$C over the coastal waters. WRF simulates a similar large-scale pressure

Fig. 8. Flight track and flight-level winds (colored; kt; a full barb ~5 m s$^{-1}$) between 100 and 225 m MSL from the Long-EZ aircraft for (a) flight 1 from 1400 to 1700 UTC 23 Jul and (b) flight 2 from 2000 to 2200 UTC 23 Jul 2014.
and surface temperature distribution across the region (not shown). In the 1.33-km WRF domain, the winds at 180 m MSL are 14–15 m s⁻¹ along the NJ coast at 2100 UTC (Fig. 7b), and there were also enhanced southerly winds just south of Long Island and along coastal southeast New England. This wind enhancement is similar to the simulated New York Bight jet enhancement in the WRF simulations presented by Colle and Novak (2010). This earlier study had limited observations to show the evolution of the jet.

Figure 8 shows the two flight tracks for sampling the jet as well as the along-track winds plotted when the aircraft was between 100 and 225 m MSL. During the first flight between 1400 and 1700 UTC 23 July (Fig. 8a), wind speeds are 5–10 m s⁻¹ from the southwest along the NJ coast. There is a slight enhancement in the wind speed to 10–12 m s⁻¹ in the New York Bight region and just south of Long Island. A north–south cross section for the leg parallel to the NJ coast shows a stable layer in the lowest 300 m (Fig. 9a), where there is a 4–5-K increase in potential temperature from 150 to 300 m; there is a mixed layer (nearly constant potential temperature) above this stable layer. This mixed layer was likely advected from the heated continental land areas (southern New Jersey). The winds in the section are strongest near the surface (~10 m s⁻¹), with little evidence of enhanced flow from south to north at this time.

During the second flight between 2000 and 2200 UTC 23 July, much stronger winds were observed along the NJ and Long Island coasts (Fig. 8b). Wind speeds were 12–15 m s⁻¹ over much of the region, with the strongest winds (17–20 m s⁻¹) over parts of the New York Bight. The south–north cross section (Fig. 9b) shows that the marine layer had increased in depth and was sloping down toward the north, with the strongest stability around 200–250 m MSL, especially in the northern part of the section. The winds had increased during the last few hours, with the largest wind speeds at 21 m s⁻¹ centered around 150 m MSL. The wind speeds increased 3–4 m s⁻¹ from south to north over a 60–70-km distance at this level, with most of the change in the first 30 km. Overall, the magnitude of these gale force winds was unexpected, especially considering they were 5–6 m s⁻¹ stronger than the models predicted (Fig. 7b).

31 July 2014: Low-level jet just east of Long Island. On 31 July 2014, there was surface high pressure (~1,020 hPa) centered just east of the mid-Atlantic coast (not shown), which resulted in large-scale southerly flow across Long Island and southern New England. The surface wind increased from 3 to 5 m s⁻¹ in the morning over the coastal waters to 5–8 m s⁻¹ by late afternoon (not shown). The Long-EZ flew along the south coast of Long Island and measured southerly wind speeds from 7 to 8 m s⁻¹ at about 30 m MSL to 10 to 11 m s⁻¹ at about 700 m MSL.

The lidar on Block Island (cf. Fig. 1) provides more temporal detail of the winds for this event from 18 to 150 m above ground level (AGL; Fig. 10). There is an increase in the wind speed from about 7 m s⁻¹ between 100 and 150 m AGL around 1800 UTC 31 July 2014 to 9–10 m s⁻¹ by 2300 UTC 31 July, with the peak winds between 2300 UTC 31 July and 0400 UTC 1 August 2014. Colle and Novak (2010) also showed this early evening wind maximum using buoy observations in this region, which is important for wind power generation since it occurs near hub height.
SUMMARY AND RESEARCH OPPORTUNITIES. The IMPOWR field study was motivated by the lack of thermodynamic and wind observations above 25 m MSL within the boundary layer over the Northeast U.S. coastal ocean. This has hindered the evaluation and improvement of planetary boundary layer parameterizations in these marine environments, which are important for wind resource assessment and forecasting in the coastal zone. The large number of days sampled with aircraft and other instruments during IMPOWR offers numerous scientific research opportunities. The IMPOWR campaign data are available by request on the data archive and portal (DAP) of the Department of Energy (at https://a2e.pnnl.gov/study).

One major question is whether mesoscale models (e.g., WRF) can accurately simulate the wind and temperature profiles in the marine boundary layer under different synoptic flow conditions. Preliminary results from IMPOWR, as shown above for the 21 June 2013 and 23 July 2014 events, suggest that WRF underpredicts the amplitude of coastal low-level jets in this region and that these jets do not extend offshore enough and are too shallow in the model. There are several other IMPOWR jet events that can be evaluated to generalize these results (Table 1). In addition, several years (2003–11) of wind observations at Cape Wind tower from 20 to 60 m have been collected to investigate the wind profile from the surface to about wind turbine hub height. This CW data and the two coastal lidars over coastal Long Island and Block Island (cf., Fig. 1) will be used to better understand the wind profiles near hub height and can be compared with the models. For example, over 90 historical WRF simulations have been completed using five different PBL parameterizations to construct a longer-term validation of WRF using these historical datasets, which will be reported in subsequent papers.

Another important question is what factors may be leading to the wind and temperature biases in the model? The WRF Model was rerun using several other PBL parameterizations for the two IMPOWR cases presented above as well as a few other events. Although there are some variations between the schemes, they all underpredict the warm-season low-level jets, which suggests that there are other factors...
that may be limiting the jet magnitude than the turbulent closure assumptions in the PBL schemes. For example, the sea surface temperatures in WRF are fixed and based on an SST product that averages a few days of satellite-derived temperatures and buoys. In reality, the SSTs in Nantucket Sound can increase by 2°–3°C during afternoon heating and can exhibit significant spatial variability near the coast. As a result, the WRF SSTs tend to be too cool during the day, which may be leading to the cool bias in all PBLs, so additional experiments are needed to determine the role of these temporal and spatial SST variations on the simulated diurnal circulations.

IMPOWR also provides useful observations to test the importance of initial conditions and mesoscale data assimilation in the coastal zone, where there are relatively sparse data to properly initialize the model. If the spread in low-level winds in WRF using these different analyses (North American mesoscale model analysis, Rapid Refresh analysis, Global Forecast System analysis, and North American Regional Reanalysis) is larger than using different WRF PBLs for a single initialization, this suggests the importance of initial conditions to these coastal wind and temperature structures. The additional observations from IMPOWR can also be ingested into WRF using an ensemble Kalman filter approach (Evensen 2003), which would test the importance of data assimilation for these coastal flows.

Last, the IMPOWR dataset is helping to expand our understanding of important structures and processes associated with coastal diurnal flows that had only been modeled in previous studies (e.g., Colle and Novak 2010). For example, IMPOWR observations are yielding important knowledge on the small-scale variations in the marine boundary layer, such as localized pressure gradient and wind enhancements, similar to those observed in the 21 June and 23 July cases above. The derived turbulent kinetic energy (TKE) from these events will help determine the importance of vertical mixing even when the marine PBL is stratified with a relatively cool SST.

The value of these IMPOWR observations, consisting of both in situ aircraft and long-term in situ observations, will not only lead to improved boundary layer parameterizations over the coastal ocean, but also hopefully motivate additional field campaigns along the U.S. East Coast to tackle other conditions. For example, the Long-EZ aircraft could not fly at night or low levels with a relatively low cloud ceiling, so a moist PBL and turbulence cannot be addressed with IMPOWR. This is important given the relatively large wind resource in these areas and the general lack of model evaluations at hub height.

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REFERENCES


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Understanding Near-Surface Stratification and Subfootprint Variability


A synthesis of present knowledge about the formation and evolution of vertical and horizontal variability in near-surface salinity at scales relevant to satellite salinity is presented.

L-band microwave radiometers on both the Soil Moisture Ocean Salinity (SMOS; Mecklenburg et al. 2012) and Aquarius/Satélite de Aplicaciones Científicas-D (SAC-D) (Lagerloef 2012) satellites have now demonstrated that they are capable of measuring sea surface salinity (SSS). They provide near-global coverage, a spatial resolution ranging from 43 to 150 km, and a precision useful for detailed oceanographic studies, that is, ±0.2 practical salinity scale (pss) [salinity is a dimensionless quantity and will be reported on the Practical Salinity Scale of 1978 (PSS-78; IOC et al. 2010, and references therein) in the rest of the text] on monthly time scales and 100 × 100 km² spatial scales (Drucker and Riser 2014; Hernandez et al. 2014; Hasson et al. 2013). This new capability provides an unprecedented global view of surface salinity, a key state variable that determines ocean circulation and is tied to the global water cycle (Reul et al. 2014c). These satellite-derived salinity data provide new insight into the spatial and temporal variability of SSS (Alory et al. 2012; Busecke et al. 2014; Hasson et al. 2014; Kołodziejczyk et al. 2015; Lee et al. 2014; Menezes et al. 2014; Qu et al. 2014; Reul et al. 2014a).

Photo: Raindrops on a water surface. [ID 5563454 ©Sailorman: Dreamstime.com]
The success of satellite salinity measurements suggests new possibilities of using global maps of salinity to monitor and understand ocean dynamics and the global hydrological cycle. However, calibration and validation of satellite-retrieved salinity is an ongoing process that requires comparison of satellite SSS values with spatially and temporally collocated in situ values. There are two key differences between

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satellite and in situ salinity. First, because of the short penetration depth of microwave radiation into the ocean (Swift 1980), microwave radiometers measure salinity in the top few centimeters of the ocean. In contrast, in situ measurements commonly used for calibration and validation (e.g., Argo floats, moorings, and ship observations) are made at depths of a few meters (Fig. 1). Second, a satellite measures salinity as a spatial average over the satellite’s footprint, whereas in situ sensors provide data at a single point [SMOS synthetic antennas have variable elliptical footprints over the field of view of 43-km resolution on average (Kerr et al. 2010), while the three beams for Aquarius are approximately elliptical and have footprints of 76 × 94, 84 × 120, and 96 × 156 km² (Lagerloef 2012)]. Therefore, if the ocean salinity field contains vertical gradients in the upper few meters, or if the ocean surface salinity has significant horizontal or temporal variability, there could be a physical difference between the satellite and in situ salinity values that would complicate calibration and validation of the satellite’s performance. The target defined for these satellite missions is to achieve a precision of 0.1–0.2 pss. This precision is sufficient to detect typical interannual SSS variability, such as that linked to El Niño–Southern Oscillation or to the Indian Ocean dipole, seasonal SSS variability in areas that have significant seasonal cycles [shown by Bingham et al. (2012) to cover 37% of the ocean surface between 60°N and 60°S and have a median seasonal SSS amplitude of 0.19 pss], mesoscale transport of salt by large eddies across strong fronts (Reul et al. 2014a; Kolodziejczyk et al. 2015), or intraseasonal SSS variability (Li et al. 2015, and references therein).

This paper synthesizes present knowledge of the processes that contribute to the formation and evolution of near-surface vertical salinity gradients and subfootprint-scale variability. The magnitude of these gradients is quantified whenever possible as a function of environmental conditions. The potential impact of both vertical salinity gradients and subfootprint-scale variability on satellite and in situ salinity data comparisons will be discussed.

**VERTICAL STRATIFICATION AND SUBFOOTPRINT VARIATIONS.** Vertical stratification in the density of the upper ocean is controlled by the vertical profiles of temperature and salinity. Vertical stratification in temperature has been extensively studied over the past several decades, as it is responsible for observed differences in sea surface temperatures derived from infrared radiometers, microwave radiometers, and in situ measurements (Minnett and Kaiser-Weiss 2012, and references therein). In contrast, relatively few studies of upper-ocean salinity stratification [see the recent climatology discussed by Maes and O’Kane (2014)] have been performed. The addition of freshwater to the ocean surface (from precipitation, river runoff, or melting of sea ice) and the removal of freshwater (through evaporation) can generate vertical salinity gradients in the upper few meters of the ocean. Vertical stratification can be strong under low wind speed conditions when there is little mixing in the

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![Fig. 2. Schematic diagrams of salinity profiles in the near-surface ocean that are relevant to interpreting satellite and in situ salinity observations. (a) The well-mixed or normal case, where the salinity is uniform as a function of depth. (b) The rain-stratified case, where the freshwater flux causes a stable density stratification to form at the surface and a decrease in salinity with decreasing depth. (c) The evaporation case, where evaporation at the water surface causes an increase in salinity with decreasing depth. Details concerning the formation of the rain and evaporation cases are provided in sections titled “Rain freshening” and “Subfootprint variability.”](image-url)
upper few meters of the ocean. When the wind speed at the ocean surface is greater than ~6 m s⁻¹, wind stress–induced momentum tends to homogenize the upper few meters of the ocean’s surface layer (Matthews et al. 2014). When cooling at the surface leads to unstable density stratification, as typically happens at nighttime, convective overturning can also generate a well-mixed surface layer. Regardless of the source of the mixing, salinity is homogeneous throughout the well-mixed layer; this homogeneous condition is considered to be the “normal” case, characterized by a salinity profile that is constant with depth, as shown in Fig. 2a. For the normal condition, radiometrically measured salinity is expected to be comparable to in situ salinity anywhere in the near-surface layer. The sections titled “Rain freshening,” “Freshwater plumes,” and “Evaporation” discuss the processes that lead to surface freshening (i.e., negative surface salinity anomalies; Fig. 2b) and surface salinification (i.e., positive surface salinity anomalies; Fig. 2c). Based on observational salinity data, the magnitudes of vertical salinity gradients during these conditions will be estimated. These processes, in particular rain freshening and freshwater plumes, are also associated with strong horizontal variability. In the section titled “Subfootprint variability,” we discuss subfootprint variability in a wider context.

Rain freshening. Salinity in the upper ocean, especially in the ocean surface boundary layer (OSBL), is subject to large spatial and temporal variability due to various contributing processes, including freshwater influx from precipitation. The scales of this variability, though not well understood or quantified, are assumed to be related to the modification of the freshwater input by the air–sea fluxes of heat and momentum, upper-ocean mixing, and advection. Low-latitude ocean regions characterized by strong rainfall, low to moderate surface winds, and high advection are therefore expected to display relatively strong spatial and temporal variability in SSS.

Under normal conditions when no rainfall is present, the OSBL is characterized by a nearly uniform density, active vertical mixing, and a high rate of turbulence dissipation (Stevens et al. 2011; Sutherland et al. 2014a). As a result, vertical salinity gradients in the upper 10 m are expected to be small (Henocq et al. 2010; Anderson and Riser 2014). In regions where normal conditions dominate, it is appropriate to neglect vertical salinity gradients when using Argo for large-scale validation of SMOS and Aquarius SSS. However, in cases where rainfall induces a near-surface vertical salinity gradient, it is possible that salinity measurements at depths of a few meters might not accurately reflect SSS measured by the satellite in the upper few centimeters. Therefore, Argo measurements made at a few meters depth might not be suitable for validating satellite measurements of SSS.

When averaged globally, rain-induced salinity stratification of the upper mixed layer creates a bias of about ~0.02 pss between the salinity measured at a few centimeters and at a few meters. Regional averaging shows that this bias increases to ~0.03 pss in the tropics (Drucker and Riser 2014). Rain-induced salinity anomalies and near-surface haloclines resulting from individual rain events were extensively observed in the western Pacific warm pool during the Tropical Ocean and Global Atmosphere (TOGA) Coupled Ocean–Atmosphere Response Experiment (COARE; Soloviev and Lukas 1996, 1997) and in the Bay of Bengal during the Joint Air–Sea Monsoon Interaction Experiment (JASMINE; Webster et al. 2002). More recently, vertical salinity gradients between the upper centimeters and a few meters depth have been observed by Argo surface temperature salinity (STS) profilers (Anderson and Riser 2014), the Air–Sea Interaction Profiler (ASIP; Ward et al. 2014; Walesby et al. 2015a; Sutherland et al. 2014b), the towed Surface Salinity Profiler (SSP; Asher et al. 2014a), shipboard thermosalinographs (TSGs) at two depths (Asher et al. 2014a), and surface drifters (Reverdin et al. 2012).

While near-surface vertical salinity gradients from individual rain-induced freshening events can be large (>1 pss between a few centimeters and a few meters), the distribution of rain events in both space and time is relatively sparse, even in regions characterized by high rainfall. For example, several recent studies have estimated that on average rain-induced surface freshening occurs ~12% of the time when considering the global ocean and ~16% of the time when considering the tropics (Boutin et al. 2013; Anderson and Riser 2014; Drucker and Riser 2014; Meissner et al. 2014). Similarly, Anderson and Riser (2014), using Argo STS float measurements, found that salinity in the upper 4 m is, in most cases, well mixed (i.e., the difference between salinity at a few centimeters and 4 m is less than 0.1 pss for 97% of the observations). Observational studies have consistently shown that, in most cases, near-surface fresh anomalies produced by rainfall are eliminated quickly (typically within a few hours) by mixing, advection, and vertical convection. For example, the deepening of fresh cells to 40-m depth has been observed in the five hours after rainfall with a surface freshening signature of 0.12 pss (Wijesekera et al. 1999; Soloviev et al. 2002).
On the other hand, Walesby et al. (2015a) observed a fresh lens that persisted for more than 15 hours, with little background mixing. The processes governing the vertical and horizontal evolution of fresh lenses are not well understood.

Several studies have attempted to quantify the difference between satellite and in situ salinity to determine the value of the rain freshening effect $\Delta S$ (pss) as a function of rainfall rate $R$ (mm h$^{-1}$) and time since rainfall. Unfortunately, both rain- and wind-generated roughness increase the microwave emissivity of the sea surface, mimicking a decrease in satellite-derived salinity measurements. Consequently, the effect of increased roughness must be addressed before determining the freshening due to rain. Although the effect of wind on roughness (and microwave emissivity) is relatively well known, rain-induced roughness is less understood.

The Aquarius instrument is useful for studying this problem because the collocated L-band radiometer and L-band scatterometer are both sensitive to changes in surface roughness, whereas the scatterometer is insensitive to changes in salinity, thereby providing the means for isolating the effects due to surface roughness. Comparison of the signals from the two instruments suggests that the increase in emissivity due to rain-generated roughness is significant at low wind speeds (Tang et al. 2013). At moderate and higher wind speeds, however, rain-generated roughness does not appear to be a major component of the total roughness (Tang et al. 2013; Boutin et al. 2014; Meissner et al. 2014).

Once roughness and atmospheric effects are removed, comparing SSS measured by SMOS (Boutin et al. 2014) or Aquarius (Drucker and Riser 2014; Meissner et al. 2014; Santos-Garcia et al. 2014) to colocated in situ salinities not under the direct influence of instantaneous rainfall shows that $\Delta S/R$ induced by rainfall is estimated to be around $-0.15$ pss (mm h$^{-1}$)$^{-1}$ (Table 1). However, this bias is an average obtained

### Table 1. The range in the rain freshening effect as a function of rain rate $\Delta S$ (pss (mm h$^{-1}$)$^{-1}$) as determined by various studies using SMOS and Aquarius data. The rain freshening effect is defined as SSS minus salinity measured at a reference depth of 5 m, and $\Delta S$ is calculated as the salinity difference as a function of rain rate.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Source for $S_{\text{REF}}$</th>
<th>Data sources</th>
<th>$\Delta S/R$ [pss (mm h$^{-1}$)$^{-1}$]</th>
<th>Range for $U'$ (m s$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMOS</td>
<td>Argo</td>
<td>Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI)</td>
<td>$-0.19^e$</td>
<td>3–12</td>
<td>Boutin et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>SMOS$^d$</td>
<td>AMSR-E</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Special Sensor Microwave Imager (SSM/I)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WindSat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquarius</td>
<td>HYCOM</td>
<td>WindSat</td>
<td>$-0.17$</td>
<td>0</td>
<td>Meissner et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Argo</td>
<td>Special Sensor Microwave Imager/Sounder (SSMIS) F17</td>
<td>$-0.13$</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$-0.07$</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Aquarius</td>
<td>Argo</td>
<td>TRMM 3B42</td>
<td>$-0.14$</td>
<td></td>
<td>Drucker and Riser (2014)</td>
</tr>
<tr>
<td>Aquarius</td>
<td>HYCOM</td>
<td>Climate Prediction Center (CPC) morphing technique (CMORPH)</td>
<td>$-0.20^f$</td>
<td></td>
<td>Santos-Garcia et al. (2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$-0.36^g$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Note that neither the SMOS nor the Aquarius salinity retrieval algorithms account for atmospheric attenuation due to liquid cloud water (LCW). It has been estimated that neglecting attenuation by LCW causes an overestimation of $\Delta S$ by approximately 10% (Wentz 2005).

$^b$ $S_{\text{REF}}$ is the reference salinity to which satellite measurements are compared.

$^c$ Term $U'$ is wind speed (m s$^{-1}$); note that not all studies resolved the dependence of $\Delta S$ on wind speed.

$^d$ Boutin et al. (2014) use as $S_{\text{REF}}$ either SMOS salinities in rain-free pixels or Argo in rain-free conditions.

$^e$ Considering various periods and various tropical regions, Boutin et al. (2014) found slopes ranging between $-0.16$ and $-0.22$, with an average of $-0.19$.

$^f$ Slope obtained in the meridional range 15°N–15°S (Santos-Garcia et al. 2014).

$^g$ Slope obtained in the meridional range 35°S–35°N (Santos-Garcia et al. 2014).
under a range of environmental conditions (wind, rain history, stratification, net heat flux, etc.). Available direct measurements of ΔS under different conditions suggest that it is unlikely that DS for a particular rain event can be accurately predicted solely by R.

Figure 3 shows the dependence of ΔS on R for the range of ΔS/R (Table 1) found from satellite SSS. Also shown is ΔS as a function of R calculated by Schlüssel et al. (1997) as part of TOGA COARE. Schlüssel et al. (1997) determined this relationship for the salinity difference between the molecular diffusion sublayer (about 50 µm) and the bulk salinity, taking into account the effects of the near-surface mixing induced by raindrops. Despite the variability found in the experimental data, the trends derived from the model and the trends derived from satellite measurements agree well. This convergence of results and theory suggests the value of −0.15 pss (mm h⁻¹)⁻¹ is relatively robust. However, at present there are no concurrent collocated in situ measurements of R and near-surface salinity profiles that include the radiometric sampling depth that can be compared with satellite-derived estimates of ΔS.

Although the molecular skin layer modeled by Schlüssel et al. (1997) is much thinner than the radiometric measurement depth used to define ΔS, it is reasonable to equate salinity across the two depths and expect the model to provide an estimate of ΔS. First, Schlüssel et al. (1997) compared their model results to salinity measured between depths of 2 and 3 cm during several rain events. They found that the magnitude of the measured salinity decrease in the upper few centimeters was consistent with their model predictions for the molecular skin layer. Second, Schlüssel et al. (1997) hypothesized that the very near surface is rapidly homogenized when near-surface mixing caused by the impact of raindrops is taken into account. This idea is consistent with the bubble population measurements made by Ho et al. (2000) that show that during rain events the upper few centimeters of the water surface are well mixed.

Further work is needed to resolve the minimum in situ sampling depth that is required to fully resolve the near-surface salinity profile. Ideally, the profile would sample up to the radiometric penetration depth (i.e., 0.01 m). As noted above, however, the kinetic energy imparted to the water surface by raindrops homogenizes the top few centimeters (Ho et al. 2000), implying that the surface is well mixed at least to the radiometric depth. Therefore, techniques that resolve the top few centimeters should be sufficient. Nevertheless, in highly resolved vertical salinity profiles measured with ASIP during two rain events, gradients larger than 0.1 pss between the sea surface and a few centimeters depth have been observed (Ward et al. 2014). ASIP profiles also show that rainfall quickly stratifies the OSBL, inhibiting turbulence. This stratification may lead to strong gradients after the rain has ceased.

Rain-induced surface freshening and the resulting stratification appear to depend nonlinearly on the freshwater input volume, the strength and direction of the surface heat fluxes, and wind-induced mixing. Asher et al. (2014a) developed a one-dimensional diffusion model that fit observed vertical salinity profiles for the top 2 m and direct measurements of R to modeled salinity profiles by tuning the turbulent diffusivity coefficient and a scale depth for mixing. This model provided the basis for developing a macroscale Rain Impact Model (RIM) by Santos-Garcia et al. (2014). RIM was developed using Aquarius data and Hybrid Coordinate Ocean Model (HYCOM) output (at ~10-m depth) from the Pacific intertropical convergence zone. It estimates the impact on Aquarius SSS based on rain accumulation over the previous 24 h and time since rainfall. The authors show that the difference between 10-m salinity and salinity measured by Aquarius is not only sensitive to R when the satellite is overhead but also to the rain history over the past 25 h, especially when wind speed is low.
Freshwater plumes. In addition to rain, other sources of freshwater to the surface ocean are river discharge and melting ice. Freshwater plumes from rivers can contribute to the formation and evolution of barrier layers (Sprintall and Tomczak 1992; Pailler et al. 1999; Mignot et al. 2007; Reul et al. 2014b). In situ measurements (e.g., hydrographic ship surveys, Argo floats, voluntary observations from buckets, or TSGs on commercial ships) are too sparse in both space and time to allow full characterization of the generation and evolution of freshwater plumes. Studies have attempted to use ocean color data from the Coastal Zone Color Scanner (CZCS) (Longhurst 1993; Muller-Karger et al. 1995) or the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; Fratantoni and Glickson 2002) to monitor the Amazon River freshwater plume. Reul et al. (2009) demonstrated the first satellite SSS retrieval by using the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) C-band and X-band channels at 6.9 and 10.7 GHz, respectively, to measure SSS in the Amazon plume. More recently, SMOS and Aquarius data have been used to detect and characterize freshwater plumes for the outflows of the Congo (Hopkins et al. 2013; Reul et al. 2014c; Chao et al. 2015), the Mississippi (Gierach et al. 2013), the La Plata (Guerrero et al. 2014), and the Amazon (Grodsky et al. 2012; Reul et al. 2014b; Fournier et al. 2015; Korosov et al. 2015).

Significant spatial and temporal variability of SSS associated with river plumes can be detected using satellite SSS in regions with large river outflows (Fig. 4). As discussed for rain, near-surface vertical salinity gradients created by freshwater plumes can complicate the comparison of satellite and in situ salinity measurements, as seen with the 2–5 pss m$^{-1}$ difference across the halocline shown by Lentz and Limeburner (1995). Plumes can also cause horizontal salinity gradients with spatial scales smaller than the footprint of the radiometers. Typical horizontal SSS gradients for the plumes from the Amazon (Lentz and Limeburner 1995) or Congo (Chao et al. 2015) exceed 0.2 pss km$^{-1}$ and extend more than 250 km from the river mouth. Therefore, in the vicinity of a river plume, a spatially sparse array of in situ sensors can indicate very different SSS variability than a satellite sensor. High-frequency SSS variations (e.g., tidal effects) can be undersampled by satellite-derived SSS products due to the relatively long revisit time of the satellite (2–3 days for SMOS and 7 days for Aquarius). At high latitudes, freshwater plumes can be caused by melting sea ice or by meltwater runoff from ice sheets, as has been observed in the seas around Greenland (Straneo and Heimbach 2013). Some of the freshest ocean waters are found in narrow high-latitude coastal currents such as the East Greenland Current. Meltwater from the Antarctic Ice Sheet is the main source of freshwater plumes in the Southern Ocean (Nicholls et al. 2009). While the direct impact of runoff on the coastal currents may be difficult to observe with satellite instruments, model simulations have shown that large meltwater runoff from the Greenland Ice Sheet changes the salinity of the seas surrounding Greenland (Marsh et al. 2010). Although these regions are poorly sampled by in situ observations, SSS retrievals for these areas from satellite L-band radiometers are now routinely available.
available (Brucker et al. 2014a). Unfortunately, the study of freshwater at high latitudes is hindered by the presence of sea ice and icebergs (Brucker et al. 2014b), low water temperature (which reduces the L-band salinity signal-to-noise ratio, thus degrading SSS retrievals), and the prevalence of very rough sea surfaces. Despite these challenges, satellites provide regular monitoring capabilities for SSS that are critically lacking in situ measurements.

**Evaporation.** Evaporation can also create vertical salinity gradients in the surface layer and, thereby, potential differences between satellite and in situ salinity measurements (Saunders 1967; Katsaros and Buettner 1969; Soloviev and Lukas 1997; Henocq et al. 2010; Anderson and Riser 2014; Drucker and Riser 2014; Asher et al. 2014b). The nature of the evaporation process and its impact, however, differs from that of precipitation in two major ways. First, evaporation increases salinity and cools the surface waters, both of which serve to increase density. This weakens or destabilizes the density gradient, thereby potentially initiating convective mixing (Yu 2010; Asher et al. 2014b; Soloviev and Lukas 2014). Conversely, precipitation freshens surface waters, reducing density, thereby strengthening the surface stratification and sustaining the freshwater lenses formed by rain (Schlüssel et al. 1997; Henocq et al. 2010; Boutin et al. 2013). Second, evaporation is almost always present, whereas precipitation occurs mostly as episodic events, although the surface freshwater volume flux during rain episodes greatly exceeds the flux due to evaporation over a time period equal to the rain event. During the TOGA COARE field experiments, Lin and Johnson (1996) observed that precipitation rates are highly variable, with peaks of 20 mm day$^{-1}$, while evaporation rates are more stable, consistently around 3–5 mm day$^{-1}$. The small volume flux, together with the destabilizing effect on the vertical density profile, implies that evaporation-induced surface salt enrichment (positive salinity anomalies) is relatively weak and short-lived (Yu 2010).

The magnitude of evaporation-induced positive salinity anomalies depends on both evaporation intensity and surface turbulence. Two processes can produce salt increase under evaporation: the salinity skin effect due to near-surface diffusive processes and the daily diurnal cycle in sea surface temperature. Saunders (1967) derived a parameterization for the change of salinity $\Delta S_{\text{skin}}$ across the salinity skin layer by scaling the layer thickness as the one-third power of the diffusivity. The mutual enhancement between evaporation and wind led him to conclude that the $\Delta S_{\text{skin}}$ is at most 2%, or around 0.07 pss for a surface salinity of 35 pss, in the extreme condition of low wind speed and large difference in air–sea specific humidity. In support of this result, Fedorov et al. (1979) obtained an estimate of $DS_{\text{skin}} = 0.12$ pss from a laboratory experiment. Yu (2010) produced a global estimate of $\Delta S_{\text{skin}}$ and suggested a magnitude of 0.05–0.15 pss. Given that the salinity skin layer is typically less than 0.1 mm thick (Zhang and Zhang 2012) and in situ instruments typically measure salinity and temperature deeper than 2 mm below the sea surface (Soloviev and Lukas 2014; Reverdin et al. 2013; Anderson and Riser 2014; Fig. 1), the salinity variations in the skin layer cannot be observed at sea. Nevertheless, Yu (2010) suggested that the salt increment in the skin layer is not a major source of error, because the salty skin layer is usually accompanied by a cooling of 0.2°–0.5°C, which is statically unstable and subject to convective overturn.

Soloviev and Lukas (1997) suggested that continuous evaporation can cause salinity to increase in the diurnal mixed layer, because the positive buoyancy flux due to diurnal heating promotes stable stratification by suppressing turbulent mixing with the water below (see Fig. 5). Confirmation of this hypothesis is provided by several field studies that have documented the existence of a relatively small salt-enhanced diurnal cycle that is present under light winds (Soloviev and Lukas 1997; Asher et al. 2014b; Drushka et al. 2014; Hodges and Fratantoni 2014). Asher et al. (2014b) reported that salt-enhanced diurnal surface lenses (0.01–0.05 pss) around 0.5 m thick are common in the subtropical North Atlantic when wind speeds are less than 4 m s$^{-1}$ and the average daily insolation is greater than 300 W m$^{-2}$. In most cases, however, the magnitude of the salinity increase is usually small, comparable to the uncertainty in the measurements (Soloviev and Lukas 2014; Anderson and Riser 2014). Thus, it is postulated that diurnal salinity anomalies are also unlikely to induce significant biases between radiometrically measured salinities and salinities measured at depths of a few meters (Asher et al. 2014b).

**Subfootprint variability.** A satellite measurement of SSS represents a near-instantaneous spatial average of the surface salinity field weighted by a function related to the satellite antenna pattern over a characteristic scale that is given by the satellite footprint. If SSS is uniform over the spatial scales averaged by a satellite, then a single in situ salinity measurement anywhere within the satellite footprint provides an accurate ground truth measurement that is representative of
the remotely sensed value. However, model simulations (Johannessen et al. 2002) have shown that the salinity field is in some places spatially or temporally inhomogeneous, so that the relationship between the instantaneous, spatially averaged salinity measured by satellite and a single in situ measurement within the satellite footprint is not well understood. In ocean regions characterized by horizontal variability with spatial scales less than the satellite footprint, the subfootprint variability could be a source of difference between satellite and in situ data. When comparing salinity data taken at a point to the spatially averaged value reported by satellite, the SSS variability within the satellite footprint (i.e., subfootprint variability) may need to be taken into consideration.

Commonly used data for purposes of calibrating and validating satellite salinity measurements are those provided by surface drifters, moored buoys in the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON), or the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) array, and, most notably, the Argo array (which as of 28 July 2015 contains 3,881 profiling floats and produces the only near-synoptic observations of upper-ocean salinity throughout the World Ocean). However, the approximate 3° × 3° spacing of

![Vertical profiles of temperature, salinity, and density obtained by averaging ship bow sensor data within 0.1-dbar pressure intervals in 10-min segments.](image)

**Fig. 5.** Vertical profiles of temperature, salinity, and density obtained by averaging ship bow sensor data within 0.1-dbar pressure intervals in 10-min segments. For plotting temporal change, successive temperature, salinity, and density profiles are shifted by 1°C, 0.5 psu, and 0.5 kg m\(^{-3}\), correspondingly. Under each profile the corresponding local solar time is given. The thin lines represent one standard deviation from the mean profiles. Note the excess salinity cumulating in the diurnal mixed layer and diurnal thermocline as a result of evaporation [after Soloviev and Lukas (1997)].
Argo profilers is a factor of 3 larger than the scale of the satellite footprints, which means that Argo does not resolve subfootprint-scale horizontal variability. Similarly, neither TAO/TRITON nor PIRATA can resolve subfootprint-scale variability in SSS.

In contrast to vertical gradients, subfootprint-scale variability in SSS can exist at all wind speeds. Both mesoscale and submesoscale features in the ocean that are responsible for the subfootprint variability of SSS are driven in large part by internal variability associated with ocean circulation. In fact, there can be significant horizontal variability on these larger scales that is not associated with vertical stratification in the upper few meters of the ocean.

Existing observational and modeling studies have provided some understanding of mesoscale and submesoscale SSS variability. For example, in a study comparing in situ data and the output of a high-resolution Massachusetts Institute of Technology (MIT) model of the Atlantic Ocean, Sena Martins et al. (2015) have shown that the annual cycle of SSS explains up to 70% of the total variability observed in some regions of the tropical Atlantic. However, this implies that in most regions at least 30% of variability is on scales other than the seasonal cycle. In fact, Sena Martins et al. (2015) show that SSS variability on time scales shorter than 30 days exceeds 0.1 pss in 42% of the $1^\circ \times 1^\circ$ grid boxes of the model. When the annual cycle is subtracted, the temporal scales of the short-term variability in the model are 4–5 days throughout the Atlantic Ocean (confirmed by results from several mooring stations), and the spatial scales vary between 10 and 150 km. Delcroix et al. (2005) used TSG measurements from the Voluntary Observing Ship (VOS) Program that have 1–3-km resolution, as well as TAO-TRITON and PIRATA moorings at daily resolution, to estimate small-scale SSS variability in the tropical oceans. They reported the mean SSS variability in $2^\circ$ (longitude) $\times 1^\circ$ (latitude) boxes over 10-day intervals to be approximately 0.2 pss. However, there are ocean regions that are characterized by much stronger spatial variability. For example, Maes et al. (2013) analyzed TSG data from the Coral Sea and reported SSS variability as large as 0.6–1 pss over spatial scales of 100 km.

Quality-controlled TSG data (Delcroix et al. 2010; Alory et al. 2015) provide a new, improved resource for estimating subfootprint, near-surface salinity variability (recognizing that TSGs typically sample at 3–7-m depth, depending on the ship, and so do not necessarily represent salinity measured by satellites). Figure 6 shows the analysis of salinity variability derived from the standard deviation within 100-km intervals along a TSG track $s_{100km}$ (data produced by Alory et al. 2015; www.legos.obs-mip.fr/observations/sss). The $s_{100km}$ values were then binned into $2^\circ \times 2^\circ$ grid boxes, and the 95th percentile value $s_{95}$ (i.e., the 95% level of the cumulative distribution of $s_{100km}$) was computed. Because the distribution of standard deviations within each grid box is not necessarily Gaussian, the average of $s_{100km}$ in a grid box does not necessarily represent the typical variability. Therefore, $s_{95}$ is shown as it represents an upper bound on the variability. Figure 6a provides a map of $s_{95}$, and Fig. 6b shows a histogram of $s_{95}$, along with the cumulative distributions of $s_{95}$ and of $2 \times s_{100km}$ (which for a Gaussian distribution of $s_{100km}$ would contain 95% of the points) overlaid. The $s_{95}$ histogram (Fig. 6b) shows a median value of 0.12 pss for the ocean regions in Fig. 6a. The cumulative distribution of $s_{95}$ is shifted to slightly larger values compared to that of $2 \times s_{100km}$ because $s_{100km}$ is skewed toward large values (Fig. 6b). However, both cumulative distributions show that in about 25% of the cases SSS spatial variability exceeds 0.15 pss over 100-km scales, and in about 10% of the cases it exceeds 0.25 pss.

Detailed analysis of $s_{95}$ regional differences (Fig. 6a) indicates that SSS spatial variability exceeds 0.5 pss in regions affected by western boundary currents, major river plumes (e.g., the Amazon), and several coastal regions, demonstrating that, in many regions, subfootprint-scale SSS variability is larger than 0.1 pss. It should be noted that the instantaneous SSS variability may differ from this map as it was made by combining variability observed during different seasons and years. Finally, patterns of subfootprint variability derived from TSG data agree with the analysis of a HYCOM ocean data assimilation product (which excluded TSG data), conducted by Vinogradova and Ponte (2012). Vinogradova and Ponte (2013) quantified SSS variability within $1^\circ \times 1^\circ$ bins to be as high as 0.2 pss near western boundary currents and in river outflow regions.

**EMERGING TECHNOLOGY TO MEASURE NEAR-SURFACE SALINITY.** L-band microwave radiometers measure salinity in the top few centimeters of the water column. Development of in situ platforms and instruments that are capable of measuring salinity at these shallow depths is a very active field of research.

On global scales, most near-surface salinity data are from the Argo profiler network. Argo floats measure salinity using a conductivity–temperature–depth (CTD) sensor with a typical uppermost measurement depth of between 3 and 5 m (Boutin and
This depth is set in order to avoid ingesting sea surface contaminants into the CTD sensor, since these contaminants would degrade sensor stability over the life span of the Argo float.

The STS sensor has recently been developed and implemented on some Argo floats (Anderson and Riser 2014; Riser et al. 2015). An STS-equipped Argo float contains a second, free-flushed, conductivity sensor that is used in conjunction with the standard CTD sensor. The STS sensor samples at 1 Hz concurrently with the standard CTD, both near the float parking depth (980–960 dbar) and again in the upper ocean (20–3 dbar) just before the standard CTD sensor is turned off. After the CTD sensor turns off, the STS sensor continues sampling as the float progresses through the ocean surface, continuing for approximately 500 s as the float prepares to transmit data. Because the STS sensor measures through the film of the ocean surface, its calibration is expected to drift due to fouling. To correct for drift, STS conductivity data are scaled to agree with the mean conductivity from the reference CTD for a region with a small temperature gradient. The resultant mean STS-derived salinity is within 0.01 pss of the reference salinity along the entire profile (Anderson and Riser 2014).

During the first Salinity Processes in the Upper Ocean Regional Study (SPURS-1) field experiment (Lindstrom et al. 2015), multiple platforms were deployed and tested, including a mooring with CTD sensors installed at depths of 0.86 and 2.1 m (Farrar et al. 2015); drifters measuring at depths of 0.5 (Centurioni et al. 2015) and 0.2 m (Reverdin et al. 2015); Wave Gliders with CTDs mounted at 0.3 and 8 m (Hodges and Fratantoni 2014); a “salinity snake” that measures salinity in the top few centimeters of the ocean (Schanze et al. 2014; Paulson and Lagerloef 1993); a surface-following towed profiler that measures salinity and temperature at four fixed depths in the upper 2 m of the ocean, with a minimum measurement depth of 0.1 m (Asher et al. 2014a,b); and ASIP, which provides vertical profiles of temperature and salinity in the upper 50 m of the ocean with vertical resolution on the order of a few centimeters and an upper depth of 0.02 m (Fig. 1). Results from the SPURS-1 field experiment are very useful to contrast these different platforms in their abilities to measure the near-surface stratification. For example, in situ platforms measuring at a single point (e.g., ASIP, STS–Argo, and Argo) undersample in terms of area coverage (except in the very special case where two adjacent Argo profilers surface at the same time when a satellite is overhead) and have time scales much longer than the satellite revisit times. Moving instruments (e.g., the Salinity Snake and ship-mounted TSGs) have better spatial coverage, but the data they provide may not be coincident or cotemporaneous with the satellite.

In situ measurement of salinity in the top few centimeters of the ocean is difficult: on nonwave-following platforms, ocean surface vertical motion
due to waves advects the water in the desired sampling region past the sensor faster than the response time of most commonly used conductivity-based salinity probes. Even platforms designed to follow large-scale wave motions at the surface have integrated measurement depths of a few centimeters (Fig. 1). Furthermore, conductivity-based salinity estimates are sensitive to the presence of bubbles, and the probes are often sensitive to fouling by biofilms, both of which are prevalent close to the sea surface. Existing methods to measure the near-surface salinity will be improved and new technologies will be developed during future field experiments (e.g., SPURS-2).

**SUMMARY AND RECOMMENDATIONS.**

The spatiotemporal variability of SSS within a satellite footprint (50–150 km) is a major issue for satellite SSS validation in the vicinity of river plumes, frontal zones, and significant precipitation. In other regions, while much reduced, this variability is often nonnegligible: in 65% of the grid boxes regularly observed by ships of opportunity (Delcroix et al. 2010), the SSS standard deviation along a 100-km transect reaches 0.1 pss. Hence, in many satellite–in situ comparisons, it is of primary importance to account for SSS variability within a satellite footprint. Information on the probability distribution function of SSS in satellite footprints is required, as are autocorrelation statistics such as those determined in some regions by Delcroix et al. (2005). Unfortunately, this variability remains very poorly documented due to the vast undersampling of the majority of the World Ocean (Fig. 6a). Clearly, knowledge of mesoscale and submesoscale SSS variability needs to be improved in terms of magnitude, spatiotemporal distribution, and related dynamics and impacts. In particular, high-resolution in situ measurements must be made in regions of strong variability. Future field campaigns such as SPURS-2 in the eastern tropical Pacific low-salinity region will enhance our understanding of small-scale SSS variability and related dynamical processes in rain-dominated regions.

Although NASA’s Soil Moisture Active Passive (SMAP) mission has a primary objective to measure soil moisture, it is possible to use SMAP data to retrieve salinity and improve the spatial sampling of SSS. The upcoming Surface Water and Ocean Topography (SWOT) satellite, to be launched in 2020, will provide sea level (and therefore derived geostrophic current) measurements that will resolve features with a wavelength of 15–100 km, which may facilitate the study of SSS variability on small scales. Emerging high-resolution modeling efforts will also give new insight into the dynamics of mesoscale and submesoscale variability of SSS. Although horizontal salinity variations are more likely to affect comparisons of satellite and in situ salinity, rainfall can in some cases produce vertical salinity gradients exceeding 1 pss m⁻¹; consequently, it is recommended that satellite and in situ SSS measurements less than 3–6 h after rain events should be considered with care when used in satellite calibration/validation analyses. Satellite SSS measurements can be expected to improve in the future, so a detailed understanding of the processes that generate and control the evolution and fate of rain-induced surface freshening events is necessary in order to optimize the use of both satellite and in situ salinity observations. Future studies should, therefore, concentrate on characterizing the vertical salinity profile between the ocean surface and 10-m depth, the penetration of raindrops within the ocean, the effects of splashing and mixing by raindrops, and the small-scale horizontal and vertical advection of freshwater anomalies at the ocean surface. Some Argo profilers enable sampling the upper 3 m of the ocean. Such efforts should be encouraged, including efforts to assess the quality of these new, near-surface measurements. Furthermore, because these processes are coupled to the air–sea fluxes of heat and momentum, it would be advantageous and prudent to perform these assessments under a range of forcing conditions, with particular attention to characterizing necessary ancillary information such as the droplet size spectrum and surface heat fluxes. Ideally, models of salinity stratification in response to precipitation, wind, and advection should reconcile surface and near-surface observations. Parameterizing the near-surface salinity stratification into a global ocean circulation model has been attempted and has shown encouraging results in comparisons with Aquarius SSS and Argo 5–10-m salinity (Moon and Song 2014; Song et al. 2015). Understanding these phenomena at the scales of both an individual rain event and a satellite pixel will help improve the parameterization of rainfall in computational fluid dynamics models.

For the upcoming SPURS-2 field experiment in 2016/17, and looking into the future, new robust salinity sensors are required. For profiling platforms, high spatial resolution is needed. For fixed-depth platforms, better quantification is needed of the actual depth range sampled by the sensor, as well as minimizing platform issues such as flow perturbations and vertical averaging.

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REFERENCES


Paulson, C. A. and G. S. E. Lagerloef, 1993: Fresh surface lenses caused by heavy rain over the Western Pacific Warm Pool during TOGA COARE, EOS Trans. AGU, 74, Suppl. to No. 43, 125.


——, Y. Quilfen, B. Chapron, S. Fournier, V. Kudryavtsev, and R. Sabia, 2014b: Multisensor observations of the Amazon-Orinoco river plume interactions with


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RONALD D. BRUNNER AND AMANDA H. LYNCH

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ANALYSIS OF AN OBSERVING SYSTEM EXPERIMENT FOR THE JOINT POLAR SATELLITE SYSTEM

by Stephen Lord, George Gayno, and Fanglin Yang

An observing system experiment was conducted to measure the impact of withdrawing data from the afternoon orbit on global forecast skill.

For more than 40 years, satellite-based observations have contributed an increasing amount of information on atmospheric temperature and moisture structure, surface state, and cloud motion (as a proxy for winds). Satellite-based soundings are primarily from radiometric instruments measuring different parts of Earth’s energy spectrum in the infrared (IR) and microwave (MW) regions. More recently, observations from the Global Navigation Satellite System (GNSS) provide accurate, unbiased thermodynamic soundings in the stratosphere and much of the troposphere through a GNSS radio occultation (GNSS-RO) technique. These satellite observations are complementary to “conventional” observations from radiosondes, surface networks, aircraft, and radars—all globally distributed but confined primarily to land areas and occasional ships. Together, they comprise the Global Observing System (GOS), which is critical for operational numerical weather prediction (NWP).

While input from the GOS is critical, both the NWP forecast model and a global data assimilation system (DAS) are also critical for accurate prediction. The DAS extracts observed information on temperature, moisture, wind, and pressure, and combines it with information from the forecast model, usually a short-term (1–6 h) forecast valid at the analysis time (Kalnay 2003), to update the model initial conditions for the next forecast cycle. Importantly, the DAS and model can also be used to evaluate the impact of observations on forecast skill. Two currently used techniques are observing system experiments (OSEs) and the forecast sensitivity to observations (FSO) technique. In an OSE, a DAS and model forecast run is conducted using a baseline set of observations;
further runs are done but with denying or adding observations to measure forecast impact through a standard set of verification scores (e.g., Kelly et al. 2004; Zapotocny et al. 2008; and many others). This method can also be used on case studies to isolate the observational impact on specific, important meteorological events [e.g., McNally et al. (2014) for Hurricane Sandy (2012)]. More recently, the FSO technique was developed. Still using a DAS, a forecast model, and observations as tools, the FSO seeks to provide information on the reduction of (typically 24 hours) forecast error, made possible by each of the input observations. FSO can be executed using adjoints of the DAS and forecast model (e.g., Langland and Baker 2004) or through ensemble-based data assimilation techniques (e.g., Liu and Kalnay 2008; Ota et al. 2013). Compared to OSEs, FSO experiments require considerably reduced computational resources but do require additional system development and maintenance for the adjoints and/or the ensemble-based DAS.

Despite the relatively straightforward nature of OSEs and FSOs, it is important to make two further comments on factors that may influence OSE and/or FSO results from different NWP systems. First, current operational global 0–5-day predictions are very accurate and, consequently, small changes to the GOS, such as the loss of one satellite instrument, may not produce a large change in forecast skill as shown by traditional mean score differences. While results have clearly shown that forecast skill in the Southern Hemisphere (SH) is more dependent on satellite data (e.g., Kelly et al. 2004), it can be more difficult to see the impact in the Northern Hemisphere (NH), since conventional observations are far more plentiful and the impact of satellite data are correspondingly less. Second, observing system impacts depend on the DAS and the forecast model used in OSE. While most of GOS is commonly ingested by international NWP systems, data assimilation and model techniques differ, and these differences can be important in determining details of the OSE impacts.

The current GOS is changing, particularly for the satellite contribution. The Joint Polar Satellite System (JPSS) is introducing a pair of advanced sounders—the Advanced Technology Microwave Sounder (ATMS) and the Cross-Track Infrared Sounder (CrIS)—that will replace the legacy operational National Oceanic and Atmospheric Administration (NOAA) Polar-Orbiting Operational Environmental Satellite (POES) instruments in the afternoon (PM) orbit. The Suomi National Polar-Orbiting Partnership (SNPP) launched the first copies of these instruments on a National Aeronautics and Space Administration (NASA) research satellite in October 2011. Since the first operational JPSS satellite may not be launched until 2017, there is concern whether the POES and SNPP instruments will cease to function before the JPSS instruments are online, which can be up to one year after launch. Therefore, the JPSS program requested the National Centers for Environmental Prediction (NCEP) to provide an OSE to determine the forecast impact of losing the data from both the POES and JPSS instruments in the PM orbit.

This paper presents results from an OSE designed to demonstrate the impact of radiometric sounder data from the PM orbit in the JPSS era. Such OSE impacts for a possible JPSS data gap have previously been reported in the literature (e.g., McNally 2012; Garrett 2013; Cucurull and Anthes 2015), but each has used a different snapshot of GOS and a different experimental focus. Garrett (2013) focused on replacement of the current MW sounder constellation by ATMS, which is only part of the JPSS instrument impact. More extensive work by McNally (2012) focused on a two-orbit configuration, and Cucurull and Anthes (2015) added possible GNSS-RO impacts to the JPSS sounder issue. Each of these studies found minor impacts in standard verification scores to the loss of PM orbit data. Here, we present a similar OSE design to McNally (2012), but it is executed with the NCEP Global Data Assimilation System (GDAS) over a much longer period, thereby allowing a more robust analysis of statistical significance and possible seasonal changes in impact. Anticipating that the results will be qualitatively similar to those from both the McNally (2012) and Cucurull and Anthes (2015) work, we give an overview of all scores to place them in context of previous results. More importantly, however, we present a more detailed statistical analysis of the representative 500-hPa geopotential height anomaly correlation (Z500AC) skill score results that relates the observing system impacts to historical accuracy data. This analysis goes beyond the traditional comparison of mean skill scores by looking at the distribution of skill scores from each OSE run and how they change as a result of retaining or removing instruments in the PM orbit. We find that such an analysis can be used quantitatively to assess changes in risk associated with any OSE results or, more generally, any comparison between NWP systems.

The “Current and future polar-orbiting satellite system” section describes current and future polar-orbiting observing systems, and the “Measuring the impact of observing systems on numerical weather prediction” section describes the OSE and FSO techniques used to measure observing system impacts. The
OSE system used in this study, including the data assimilation and forecast system, is described in the “Description of the NCEP OSE system” section. The “OSE setup” section describes the control and experiment, and the next several sections present the evaluation procedures, overview of results, and a more detailed analysis of the Z500AC skill score distributions, respectively. The last section contains the summary and a short discussion. Appendix A summarizes the global observations available for this OSE, and appendix B provides some further background information and context for interpreting the forecast impacts presented in this paper.

THE CURRENT AND FUTURE POLAR-ORBITING SATELLITE SYSTEM. The satellite-based observing system (Fig. 1) is a critical component of GOS that supports routine operational weather prediction. For reference, a list of the primary GOS observations used by NCEP in 2012–13 is in appendix A. Because conventional observing systems, such as radiosondes, are mostly confined to continental areas and a few isolated islands and mobile platforms aboard ships, oceanic thermodynamic observations throughout the vertical atmospheric column are obtained almost exclusively from radiometric sounders on polar-orbiting satellites. Geostationary satellites, stationed over the equator at various longitudes, provide valuable imagery over the global domain and derived wind estimates from that imagery, but currently they carry only low-vertical-resolution infrared sounders that do not provide much information useful for NWP. Polar-orbiting satellites also host the GNSS-RO instruments that provide highly accurate and complementary atmospheric soundings.

Global coverage by atmospheric sounders is achieved through sun-synchronous (polar) orbits with different nominal equatorial crossing times (Fig. 1). Three polar orbits—PM, midmorning (mid-AM), and early morning (early AM)—provide complete global coverage every 6 h, while two orbits cover approximately 85% of Earth’s surface (Fig. 2). Current international agreements have NOAA providing coverage from the PM orbit and the Meteorological Operational (MetOp) system, sponsored by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), occupying the mid-AM orbit. Research satellites from NASA, the European Space Agency (ESA), and the European Commission (EC) may occupy either orbit. Operational U.S. Department of Defense (DOD) satellites have occupied a third (early AM) orbit (not shown). [Courtesy of NOAA/National Environmental Satellite, Data, and Information Service (NESDIS).]

Fig. 1. The satellite-based observing system. Polar-orbiting satellites (red) are distinct from those in geostationary orbits (white) and are defined by their equatorial crossing time. Being in a sun-synchronous orbit, the satellite achieves global coverage as the Earth rotates beneath the orbit, which takes approximately two hours to complete. NOAA operational satellites generally occupy the PM orbit, while MetOp (EUMETSAT) satellites occupy the mid-AM orbit. Research satellites from NASA, the European Space Agency (ESA), and the European Commission (EC) may occupy either orbit. Operational U.S. Department of Defense (DOD) satellites have occupied a third (early AM) orbit (not shown). [Courtesy of NOAA/National Environmental Satellite, Data, and Information Service (NESDIS).]
improved instrument characteristics, including higher horizontal and vertical resolution and lower noise (e.g., Goldberg et al. 2013; Kim et al. 2014; Han et al. 2013; Zavyalov et al. 2013). In addition, the NASA research satellite *Aqua* provides observations from the hyperspectral Atmospheric Infrared Sounder (AIRS) and a partially operating AMSU-A in the PM orbit. In Europe, EUMETSAT launched its first polar-orbiting satellite *MetOp-A* in October 2006 with an AMSU-A, an MHS, and the hyperspectral Infrared Atmospheric Sounding Interferometer (IASI). Also on *MetOp-A* are the Advanced Scatterometer (ASCAT), the GNSS Receiver for Atmospheric Sounding (GRAS), and the Global Ozone Monitoring Experiment (GOME) for measuring surface winds, GNSS-RO, and ozone, respectively. *MetOp-B* was launched in September 2012 with the same sounding instruments. Currently, the Defense Meteorological Satellite Program (DMSP) satellites occupy the early-AM orbit and host the Special Sensor Microwave Imager/Sounder (SSMIS), which has some sounding channels similar to those on AMSU-A. However, the DMSP platforms are also nearing the end of their life cycles and the future of instrument(s) in the early-AM orbit is uncertain.

The future operational polar-orbiting satellite sounding system therefore will be primarily composed of JPSS and MetOp satellites in the PM and mid-AM orbits, respectively. Each satellite will have an MW and hyperspectral IR sounder, thereby forming a two-orbit, four-sounder (2O–4S) configuration. In the PM orbit, ATMS and CrIS have strong credentials, but nevertheless they are of approximately the same sounding capability as the current AMSU-A/MHS and AIRS. It is important to take note of these similarities in designing impact experiments for the future polar-orbiting satellite system.

**Fig. 2.** Polar-orbiter observation coverage, illustrated using AMSU-A as an example, for a 6-h window centered on 1200 UTC 1 Jun 2011. Coverage shows the (a) PM, (b) mid-AM, (c) mid-AM and PM, and (d) mid-AM, PM, and NOAA-15 orbital combinations. Because of its long-term drift from the PM orbit, NOAA-15 is a proxy for the early-AM coverage. Colors depict differences between the observed channel-9 bias-corrected radiance value and the collocated GFS background (6-h forecast) value calculated with the operational CRTM.
MEASURING THE IMPACT OF OBSERVING SYSTEMS ON NUMERICAL WEATHER PREDICTION. There is considerable interest in the meteorological community and elsewhere about the impact of various GOS components on daily operational weather prediction skill, particularly in this period of rapid change in the satellite observing system. The World Meteorological Organization has sponsored international workshops every 4 years (e.g., Böttger et al. 2004; Pailleux et al. 2008; Andersson and Sato 2012) to review progress in observing system impacts for NWP. Testing the impact can be done in several ways by OSEs and the FSO technique, which differ in their approach but nevertheless use the power of modern data assimilation systems as their core software. In a typical OSE (e.g., Kelly et al. 2004; Zapotoczny et al. 2008; McNally 2012; Cucurull and Anthes 2015), a control data assimilation and forecast experiment is conducted with all observations, and a second experiment is run without the observations of interest or with new observations added. Differences in performance skill are typically measured with standard scores such as the Z500AC (WMO 2010), root-mean-square (RMS) differences against both gridded analyses (GRD; RMS-GRD) and observations (OBS; RMS-OBS), and equitable threat scores (ETS) for precipitation (Wilks 1995).

FSO calculations measure the percentage contribution to the reduction of forecast error from each observation source (Langland and Baker 2004; Cardinali 2009; Gelaro and Zhu 2009; Ota et al. 2013; Lorenc and Marriott 2014). While OSEs and FSO studies have very different theoretical and algorithmic bases, they give consistent results on the relative importance of the most impactful observing systems (Gelaro and Zhu 2009) if the same data assimilation system is used. Nevertheless, OSEs and FSO studies from different data assimilation systems are not entirely consistent. For example, Joo et al. (2012) and Ota et al. (2013) report different rank orders of sensitivity using an FSO technique (Table 1). Some reasons for these discrepancies are discussed below.

While the design and execution of OSEs and FSOs are relatively straightforward, the results and their interpretation can be subject to many factors, including the representativeness of the analysis and forecast sample, and the overall quality of the analysis–forecast system (A-FS), including any forecast model bias. As also discussed by Cucurull and Anthes (2015), these factors cause forecast skill to depend on the season and meteorological conditions, so that details of observation impacts can also depend on the time period chosen for the experiment. To mitigate this dependency and to expose the NWP system to as many different weather regimes and observations as practical, experiments of at least 4–6 weeks for both winter and summer seasons are often conducted. Some OSEs are configured as case studies and can thereby directly illustrate forecast impacts on societally important meteorological events (e.g., McNally et al. 2014). However, case studies do not provide a statistically significant sample for overall impact and can often show no impact or even negative impact (the forecast is better without the observations in question; J. Yoe 2012, personal communication).

Accuracy of the A-FS and the details of observation processing are other important factors in determining the impact of observations. Some of these details include error assigned to the various observation types, quality control techniques and thresholds, and data thinning. Since the purpose of assimilating observations is to correct initial condition errors, a less accurate A-FS or larger assigned observation error may require more or different observations to achieve those corrections and, therefore, the overall observation impact can differ. Finally, the GOS information derives from different sources, some of which may add complementary information (as they have different observing techniques, and horizontal and vertical resolutions), but some may add resilience to the GOS by providing increased sampling over the globe. In the latter case, loss of one instrument of several similar ones can often be compensated by the DAS extracting additional information from the remaining instruments (Andersson and Sato 2012). For example, in 2012–13, five AMSU-A instruments provided operational data from (effectively) three different orbits (Table A1). In this case, withdrawal of one or more AMSU-A instruments may not impact the mean forecast skill in an OSE. In summary, quantitatively comparing OSEs should be done with caution, with an emphasis on a thorough understanding of the results.
DESCRIPTION OF THE NCEP OSE SYSTEM.

Model and data assimilation. The NCEP operational global modeling system, as implemented on 22 May 2012, was used to execute the OSEs; its main components are the Global Forecast System (GFS), version 9.0.0, and the Gridpoint Statistical Interpolation analysis system (GSI), version 3.3. The GFS 9.0.0 is a global atmospheric spectral prediction model at 27-km (T574) resolution and 64 vertical levels (see [www.emc.ncep.noaa.gov/GFS/doc.php](http://www.emc.ncep.noaa.gov/GFS/doc.php) for details). The GSI is a 3D hybrid (ensemble–variational) analysis system that provides the initial condition for the GFS from a blend of a first guess (a previous 9-h forecast) and both conventional and satellite observations within a 6-h data window, ±3 h from the analysis time (Parrish and Derber 1992; Derber and Wu 1998; Kleist et al. 2009). The background error is estimated by a GSI ensemble composed of 80 members executing at 55-km (T254) resolution (Kleist and Ide 2015; Wang et al. 2013). An ensemble Kalman filter (EnKF) generates flow-dependent, ensemble-based background error covariance estimates and a hybrid algorithm, using both static and ensemble-based background error estimates, is used to determine the analysis.

Satellite observations are assimilated as clear-sky radiances (Derber and Wu 1998; McNally et al. 2000), using the Community Radiative Transfer Model (CRTM) from the Joint Center for Satellite Data Assimilation (Chen et al. 2008, 2010). Quality control rejects cloud-contaminated observations detected in the infrared sensor data (Eyre and Menzel 1989). For thin clouds in the microwave, the retrieved cloud liquid water (Grody et al. 2001) is used as a bias correction predictor to remove the cloud radiative effect. GNSS-RO observations were assimilated as in Cucurull and Derber (2008) and later upgraded (Cucurull 2010; Cucurull et al. 2013).

The OSE was run using the same analysis–forecast (“cycled”) configuration as NCEP’s operations; a brief summary of that procedure follows. Four times per

<table>
<thead>
<tr>
<th>Observation system</th>
<th>Orbit</th>
<th>CNTL</th>
<th>NOPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMVs (Aqua)</td>
<td>PM</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>AMVs (Terra)</td>
<td>AM</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>MetOp-A ASCAT</td>
<td>Mid-AM</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>MetOp-A IASI</td>
<td>Mid-AM</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>MetOp-A AMSU-A</td>
<td>Mid-AM</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>MetOp-A MHS</td>
<td>Mid-AM</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Aqua AIRS</td>
<td>PM</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>NOAA-19 AMSU-A</td>
<td>PM</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>NOAA-19 MHS</td>
<td>PM</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2. List of polar-orbiting observations selected for the CNTL and NOPM experiments.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH-Z500-AC</td>
<td>500-hPa geopotential height anomaly correlation, NH and SH, for 24–240-h forecast period</td>
</tr>
<tr>
<td>SH-Z500-AC</td>
<td></td>
</tr>
<tr>
<td>NH-MSLP-AC</td>
<td>Mean sea level pressure anomaly correlation, NH and SH, for 24–240-h forecast period</td>
</tr>
<tr>
<td>SH-MSLP-AC</td>
<td></td>
</tr>
<tr>
<td>NH-T-RMS-GRD</td>
<td>RMS error for temperature, NH and SH, for 24–240-h forecast period vs gridded analysis every 50 hPa from 850 to 100 hPa</td>
</tr>
<tr>
<td>SH-T-RMS-GRD</td>
<td></td>
</tr>
<tr>
<td>NH-W-RMS-GRD</td>
<td>RMS error for wind, NH, SH, and TR, for 24–240-h forecast period vs gridded analysis every 50 hPa from 850 to 100 hPa</td>
</tr>
<tr>
<td>SH-W-RMS-GRD</td>
<td></td>
</tr>
<tr>
<td>TR-W-RMS-GRD</td>
<td></td>
</tr>
<tr>
<td>CONUS PRC 24-48h</td>
<td>ETS for precipitation over CONUS for 24–48- and 60–84-h forecast periods</td>
</tr>
<tr>
<td>CONUS PRC 60-84h</td>
<td></td>
</tr>
<tr>
<td>Hur-TRK-ATL</td>
<td>Hurricane track errors for Atlantic basin</td>
</tr>
<tr>
<td>Hur-TRK-EPAC</td>
<td>Hurricane track errors for east Pacific basin</td>
</tr>
<tr>
<td>NH-W-RMS-OBS 24-48h</td>
<td>RMS error of wind vs radiosonde observations for TR, NH, SH, and NA for 24–48-h forecast period and for every 25 hPa from 1000 to 100 hPa</td>
</tr>
<tr>
<td>SH-W-RMS-OBS 24-48h</td>
<td></td>
</tr>
<tr>
<td>TR-W-RMS-OBS 24-48h</td>
<td></td>
</tr>
<tr>
<td>NA-W-RMS-OBS 24-48h</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Standard verification scores for NH, SH, TR, CONUS, NA, and various hurricane basins. All verification is against ECMWF analyses, except for precipitation, hurricane track, and RMS vs observations.
day (0000, 0600, 1200, and 1800 UTC), at approximately 3 h after cycle time, the GSI creates initial conditions for the GFS forecast model, which is run to 16 days. This is known as the “GFS” cycle. Then, at approximately 6 h after cycle time, the GDAS cycle begins with the GSI, creating another analysis using additional, late arriving data unavailable to the GFS cycle. The GDAS analysis is the initial condition for a 9-h forecast that serves as the first guess for the next GFS and GDAS cycles.

Observations selection. The observations selection for the OSE follows closely the choices of McNally (2012), bearing in mind that that study covered 3 months (December–February) of winter 2009/10. Conventional observations of all types (Table A1) are assimilated in all experiments, including globally distributed radiosondes, aircraft, and both overland and marine surface observations. Satellite data from geostationary and GNSS-RO sources are also assimilated in all experiments. Polar-orbiting instruments are selected as follows (see Table A1) and as summarized in Table 2. To simulate the 2O–4S configuration in the future JPSS era, MetOp (IASI, AMSU-A, and MHS) instruments are used from the mid-AM orbit and in the PM orbit Aqua (AIRS) and NOAA-19 (AMSU-A and MHS) are selected as the PM sounding instruments for the OSE control (CNTL) run. Since the experiment was designed before the SNPP CrIS was assimilated operationally by NCEP, we used Aqua AIRS, in the PM orbit as proxy for the CrIS. Note that AMSU-A and MHS combined have approximately the same spectral coverage as ATMS. Note also that MHS is not present on Aqua and that Aqua AMSU-A does not have a complete set of channels operating, thereby making NOAA-19 instruments the preferred MW choice for the PM orbit. While we recognize that ATMS and CrIS are, in fact, superior instruments, we do not expect an OSE using these NOAA-19 and Aqua proxies to yield substantially different results. In the no PM orbit (NOPM) OSE run, which simulates the absence of data in the PM orbit, all CNTL observations from NOAA-19 and Aqua [AIRS and atmospheric motion vectors (AMVs)] are omitted from the data assimilation under the assumption that neither sounders nor an imager (for AMVs) will be in orbit for the NOPM scenario. AMVs from Terra were not available over the OSE time period. The MetOp scatterometer, ASCAT, was used in all runs.

For future reference, note that NCEP operations used the following additional satellite data (see Table A1): Aqua (AMSU-A), NOAA-18 (AMSU-A, MHS), NOAA-15 (AMSU-A), and HIRS on both NOAA-17 and NOAA-19. NOAA-18 observations are in the PM orbit (same as Aqua and NOAA-19), so they

| Table 4. Statistical breakdown (%) of highest and lowest Z500AC scores among the CNTL, NOPM, and OPS runs for each verification date accumulated hemispherically. Each hemisphere had 293 cases. |
|---------------------|---------------------|---------------------|
|                     | OPS                 | CNTL                | NOPM                |
| NH                  |                     |                     |                     |
| Highest             | 40.2                | 34.5                | 25.3                |
| Lowest              | 32.4                | 30.4                | 37.2                |
| SH                  |                     |                     |                     |
| Highest             | 39.2                | 34.1                | 26.6                |
| Lowest              | 26.3                | 27.0                | 46.7                |

1 For the MW instrument, we used NOAA-19 AMSU-A and MHS instead of ATMS because it was originally planned to run an additional experiment to substitute ATMS for the NOAA-19 MW instruments. However, this experiment was never executed due to the unavailability of computing and personnel resources.
are largely redundant and therefore add less additional information for data assimilation (EUMETSAT 2011). Compared to the hyperspectral information from AIRS and IASI, HIRS data provide relatively insignificant information. NOAA-15 data coverage, on the other hand, does contribute by filling the uncovered area between the AM and PM orbits, so it effectively is an early-AM instrument as noted earlier (Fig. 2). NCEP did not use DMSP SSMIS data operationally until February 2015 and therefore the data were not included in this OSE.

OSE SETUP. The GDAS for both the CNTL and NOPM runs began on 0000 UTC 15 July 2012 and ended 7 months later on 0000 UTC 15 February 2013. Results in this paper cover the period 0000 UTC 1 August to the end of the runs in February; the July period is a spinup for all runs. The GFS forecast was run four times daily from the experiment’s beginning until 3 November 2012 in order to generate the maximum number of global forecasts with hurricanes; thereafter, until 15 February 2013, the GFS forecast was run once per day at 0000 UTC. A total of 293 10-day forecasts were made. While typical NCEP OSEs are run for 4–6 weeks for two seasons, this OSE extends for 7 months over three seasons and is one of the longest performed by NCEP. As such, it provides an opportunity to measure the impact of observations across different seasons with a continuous GDAS run and to assess the statistical significance with a very large number of cases. The CNTL and NOPM experiment differ only in the polar-orbiting observations omitted from the data assimilation in the NOPM experiment

Fig. 4. Average (top) NH and (bottom) SH 0000 UTC Z500AC forecast scores for 1–10 days over SON for CNTL and NOPM. The lower panel of each plot shows the difference between CNTL and NOPM. Differences outside of the boxes are statistically significant at the 95% level.

2 While the GFS forecast is run to 16 days in operations, the 10-day forecast for this OSE covers the most skillful part of the forecast that is most sensitive to, and appropriate for showing, the impact of observations and initial conditions on forecast accuracy.
(Table 2). Furthermore, we enhance the evaluation of the CNTL and NOPM runs with results from NCEP’s operational (OPS) run, which was executed with the same model and data assimilation system and included all the observation sources listed in appendix A (see Table A1).

**EVALUATION PROCEDURES.** A complete evaluation of all the OSE results is very complex and demanding, and is beyond the limited scope of this paper. As noted earlier, differences in skill are customarily measured by standard NWP scores, including the Z500AC, which is an overall measure of the skill (appendix B).

Other standard statistical measures (Table 3) are summarized here and can provide supporting evidence by measuring different aspects of the model forecast output, for example, precipitation ETS and hurricane track errors. The evaluation covers almost three seasons and thereby captures seasonal variability, if any. Choosing representative case studies is a very subjective process, with its own challenges, and will not be attempted here since the focus is on the quantitative and objective information that can be gleaned from a more detailed analysis of the Z500AC score alone.

Standard verification scores (Table 3) were used to evaluate forecast skill for each run. Anomaly correlation and some RMS scores were verified against analyses. To provide an independent analysis estimate, the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis was used as verification for geopotential height, temperature, and winds. Forecast verification for longer than 3 days using either the GDAS or a multicenter analysis does not change the results presented here simply because the forecast errors are much larger than any analysis differences. To verify precipitation, the NCEP Climate Prediction Center daily precipitation analysis, assembled from over 10,000 conterminous United States (CONUS) 24-h rain gauge reports, was used. Hurricane track scores, verified against National Hurricane Center best-track data for the Atlantic (ATL) and east Pacific (EPAC) basins, were accumulated from the four-per-day forecasts through 120 h. Short-term (24–48 h) temperature and wind forecasts were also verified against radiosonde observations in the NH, SH, tropics (TR), and North America (NA). All other statistics were generated from forecasts initiated at 0000 UTC 1 August 2012 to 0000 UTC 15 February 2013 for 0000 UTC and 1200 UTC 1 August to 1200 UTC 2 November 2012 for 1200 UTC. Statistical significance at the 95% confidence level was determined by a Student’s t test (Hogg and Craig 1978) for all scores except for precipitation ETS listed in Table 3. For ETS, a Monte Carlo resampling method (Hammersley and Handscomb 1975) with 10,000 realizations was used to determine its confidence level. A qualitative scorecard was generated to provide an overview of all results.

For an additional perspective on the OSE impacts, these scores are compared with the annual distribution of 5-day Z500AC scores from the operational GFS (appendix B), the annual mean history of which is characterized by an increase of skill over time (Fig. B1). Furthermore, the distribution of Z500AC scores (Fig. B2) shows that, over the period 1996–2014, the percentage of low scores has decreased remarkably, while the percentage of high scores has increased. In this paper, we explore whether similar trends accompany changes to the satellite observing system, such as those tested with this OSE.

**OVERALL RESULTS.** Since a quantitative comparison of OSE results creates an enormous set of scores for different forecast variables, times, and model levels, the focus here is on the 5-day Z500AC score because it is an overall indicator of forecast quality in the extratropics and is commonly used for NWP model comparisons (Simmons and Hollingsworth 2002).

The NH and SH 5-day Z500AC time series (Fig. 3) shows that each of the CNTL, NOPM,
and OPS runs have the highest or lowest scores at multiple times throughout the experiment period. Although there are episodic outlier results for the CNTL and NOPM runs—for example, late August in the SH (NOPM), from mid-September through mid-October in the NH (NOPM), and late January in the NH and SH (CNTL)—it appears visually that the performance of each of the three runs is almost indistinguishable from the others; that is, no run is superior throughout the entire time series. To confirm this fact, scores were compared head to head for each verification time. A frequency breakdown of the highest and lowest scores for all runs (Table 4) shows that the NOPM produces the smallest percentage of the highest scores in both hemispheres and the largest percentage of the lowest scores. The latter impact is stronger in the SH, where there are many fewer nonsatellite observations and the influence of satellite data is correspondingly larger as expected.

Over the entire experiment, the mean 5-day Z500AC score for 0000 UTC initial conditions (Fig. 3) is 0.005 and 0.013 larger for CNTL than for NOPM in the NH and SH, respectively—about equal to approximately one year of increase in the GFS annual mean Z500AC (appendix B). While the differences in CNTL and NOPM 5-day Z500AC scores appear to be small, if not underwhelming, they persist throughout the entire 1–10-day forecast period (Fig. 4) and are statistically significant at the 95% confidence level for 1–8 days in the NH and 1–5 days in the SH over

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**Table 5. Quintile cutoff values for 5-day Z500AC for CNTL based on the 293 cases, including 0000 and 1200 UTC; e.g., the lowest quintile for the NH has a maximum value of 0.835931.**

<table>
<thead>
<tr>
<th>Category (%)</th>
<th>Description</th>
<th>Upper cutoff value</th>
<th>NH</th>
<th>SH</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>Worst</td>
<td></td>
<td>0.835931</td>
<td>0.814969</td>
</tr>
<tr>
<td>21–40</td>
<td>—</td>
<td></td>
<td>0.869417</td>
<td>0.844165</td>
</tr>
<tr>
<td>41–60</td>
<td>—</td>
<td></td>
<td>0.892238</td>
<td>0.869863</td>
</tr>
<tr>
<td>61–80</td>
<td>Good</td>
<td></td>
<td>0.915522</td>
<td>0.895398</td>
</tr>
<tr>
<td>81–100</td>
<td>Best</td>
<td></td>
<td>1.000000</td>
<td>1.000000</td>
</tr>
</tbody>
</table>

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Fig. 6. Skill distribution of 5-day Z500AC scores for CNTL, NOPM, and OPS scores for (top) 0000 and (bottom) 1200 UTC in (left) NH and (right) SH. The 1200 UTC runs were produced only through 3 Nov 2012, so they do not include winter scores. Scores from each experiment are distributed into 20 bins of width 0.05 between 0.025 and 0.975. The abscissa is the Z500AC binned score, and the ordinate is the percentage in each bin.
the September–November (SON) part of the experiment. From December to February (DJF; not shown), the CNTL Z500AC scores were significantly higher for 1–10 days only in the SH. In August (also not shown), the NH Z500AC scores were not significantly different, but the CNTL score was significantly higher for 1–3 days in the SH.

The comparison of overall CNTL and NOPM 1–10-day forecast performances is summarized by a scorecard (Fig. 5) showing superiority and any statistical significance for all scores (Table 3) over three subperiods: August only (AUG), SON, and DJF. In the NH, the CNTL is consistently superior at all forecast times for Z500AC, mean sea level pressure anomaly correction (MSLP-AC), and RMS-GRD scores, but it is significantly better for SON only. In the SH, where differences between the CNTL and the NOPM are larger, the CNTL is significantly better for both SON and DJF. CONUS precipitation scores for the CNTL are either neutral or insignificantly better for most subperiods, but they are worse for 60–84 h in DJF. Tropical RMS-GRD wind scores are not significantly better. Hurricane track errors for the CNTL are better in the ATL basin but neutral in the EPAC basin. A greater number of scores are statistically significant in the SH than in the NH, as might be expected due to the higher reliance on satellite data in the SH. Overall, statistically significant results are mostly found in SON and DJF but rarely in AUG, presumably because the number of AUG verifying times is much smaller. RMS-OBS scores for 24–48 h are mostly neutral (or not significant), the exception being SH winds. Interestingly, the statistical significance for NH Z500AC and other scores changes from significant in SON to insignificant in DJF; the reason for this change is not readily apparent.

The OPS mean 0000 UTC Z500AC score for the entire experimental period is 0.002 and 0.001 higher than CNTL in the NH and SH, respectively (Fig. 3). Compared to the CNTL experiment for all verification dates, OPS produces about 5% more instances in both hemispheres when it has the highest score (Table 4), but OPS also has about the same fraction of the lowest scores. Despite having about the same fraction of the lowest scores in a head-to-head comparison, it is interesting to note that the OPS time series also does not have any episodic low-score outliers. We speculate that this additional resilience of the OPS observing system (Andersson and Sato 2012), by having more AMSU-A instruments in orbit relative to the future 2O–4S configuration, has the potential to increase skill marginally in the time mean, but more importantly it may reduce the possibility of an episodic low-score forecast.

ANALYSIS OF SKILL DISTRIBUTION. After accounting for seasonal skill changes by collecting scores over a calendar year, the Z500AC skill distribution appears to be characteristic of a particular NWP system (appendix B). GFS improvements over the period 1996–2014 have resulted in a reduction of low scores and an increase in high scores. Since changing the observing system constitutes a change to the NWP system, we are motivated to apply the skill distribution analysis described in appendix B to the CNTL, NOPM, and OPS runs.

The OPS and CNTL skill distributions are very similar (Fig. 6), except at 1200 UTC in the NH, and markedly different from NOPM. The impact of removing the PM orbit is clearly seen as a shift in the distribution toward

<table>
<thead>
<tr>
<th>Platform</th>
<th>Instrument/measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional</strong></td>
<td></td>
</tr>
<tr>
<td>Soundings</td>
<td>Balloon</td>
</tr>
<tr>
<td>Ship</td>
<td>Radiosonde</td>
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<tr>
<td>Pibals</td>
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<td>Commercial aircraft</td>
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<td>Canadian AMDAR</td>
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<td>European AMDAR</td>
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<td>Pilot reports</td>
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<td>Land surface</td>
<td>Airport surface data</td>
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<td>ASOS and AWOS</td>
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<td>Drifting buoy</td>
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increased frequency of low scores for both 0000 and 1200 UTC and in both hemispheres. It is more noticeable in the SH, where the influence of satellite data is larger and the time-mean loss of skill due to removing the PM orbit is correspondingly larger. Indeed, mean skill differences over the experimental period due to loss of the PM orbit (Fig. 4) show up more clearly in Fig. 6 as shifts in the NOPM skill distribution that are particularly evident at the tails of the distribution, that is, for the lowest and highest forecast scores. The shortened 1200 UTC time series does not include November–February cases, resulting in a smaller sample size by more than 50% and a broader NH skill distribution as shown (Fig. 6, bottom left) that is most likely a result of the smaller sample. The impact of additional instruments in OPS, relative to the CNTL, is present in the form of slightly more higher-than-average scores in the NH and fewer low scores in the NH and SH at 0000 UTC.

To quantify the abovementioned results, we divide the CNTL score distribution into quintiles, each with 20% of the total number of forecast scores (Table 5). The shape of this CNTL distribution is described by the quintile boundaries and is a reference against which the NOPM and OPS are then compared. For the sake of brevity, we label forecasts in the lowest quintile as the “worst” of the CNTL distribution and the two highest quintiles as the “good” and “best” forecasts, respectively. Measuring the shifts of both NOPM and OPS skill distributions relative to the reference CNTL quintiles gives quantitative statements about the tails of the distributions, which (as noted previously) represent the probability of a worst or best GFS forecast.

The changes in skill distributions (Fig. 7) are calculated by determining the percentages of NOPM and OPS forecasts in each of the CNTL quintiles defined in Table 5. Relative to CNTL, NOPM is 13.6% more likely to produce a worst GFS forecast in the NH and 35.6% more likely to do so in the SH. For best GFS forecasts, NOPM is 11.9% less likely to populate the upper 20% of CNTL scores in the NH and 18.6% less likely in the SH. OPS changes relative to CNTL are less dramatic but nonetheless consistent with previous statements associated with Fig. 6. The additional observations in OPS reduce the likelihood of worst GFS forecasts in both the NH (13.6%) and SH (10.2%) but have little overall impact on improving the best GFS forecasts in either hemisphere. Instead, reductions in frequencies of the lowest 40% of CNTL SH scores of 10.2% and 13.8% show up as a large frequency increase (27.1%) in the middle quintile of the CNTL skill distribution.

**SUMMARY AND DISCUSSION.** An OSE using the NCEP GFS has been designed and executed to measure the potential impact of the loss of PM polar-orbiting observations in the future 2O–4S configuration of the JPSS era. The control (CNTL) ingested observations from the operational GOS, including those from a polar-orbiting MW (temperature and moisture) sounder and

<table>
<thead>
<tr>
<th>Platform</th>
<th>Instrument/measurement</th>
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<tr>
<td>NASA Aqua</td>
<td>AIRS</td>
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<td></td>
<td>AMSU-A</td>
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<td></td>
<td>MODIS (AMVs)</td>
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<td>SNPP</td>
<td>ATMS</td>
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<td>GNSS-RO COSMIC-1</td>
<td>RO</td>
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<tr>
<td>TerraSAR-X</td>
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<td>SAC-C</td>
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<td>C/NOFS</td>
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<td>NASA Aura OMI</td>
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<tr>
<td>NOAA GOES GOES-13</td>
<td>Sounder</td>
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<td>Imager (AMVs)</td>
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<td>GOES-15</td>
<td>Sounder</td>
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<td>Imager (AMVs)</td>
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<td>EUMETSAT Meteosat-10</td>
<td>SEVIRI (Imager)</td>
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<td>SEVIRI (AMVs)</td>
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<td>Meteosat-7</td>
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<td>JMA MTSAT-2</td>
<td>Imager (AMVs)</td>
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* NOAA-17 HIRS was assimilated until 13 Dec 2012.
a hyperspectral IR sounder in both the mid-AM and PM orbits. The PM instrument data were removed from the NOPM run. Data used were from the operational observations received by NCEP in the period 2012–13.

Removing PM orbit satellite observations results in generally inferior standard scores in the NH and SH, with the impact being greater in the SH. The NOPM experiment has inferior mean anomaly correlation and RMS scores, and these differences are statistically significant in SON in the NH and in both SON and DJF in the SH. Precipitation, tropical wind scores, and hurricane track errors are not significantly impacted although the trend is toward some degradation. These results, including the larger SH impact and more significant extratropical impact, are generally consistent with those from other OSEs over the last decade (Zapotocny et al. 2008; McNally 2012). Comparing the OSE CNTL with NCEP’s OPS, it appears that adding three AMSU-A MW sounders increases the mean Z500AC score incrementally, but not significantly, in both hemispheres.

Analysis of the skill distributions for each of the CNTL, NOPM, and OPS runs is more revealing. Comparing CNTL and NOPM, removing the PM orbit data produces notable shifts toward increases in the number of low scores and clear decreases in the number of the highest scores. NOPM is 13.6% more likely to produce a worst GFS forecast in the NH and 35.6% more likely to do so in the SH. NOPM is 11.9% less likely to populate the upper 20% of the CNTL scores in the NH and 18.6% less likely in the SH. Comparing CNTL and OPS, there is a decrease in the likelihood of generating low scores in OPS of 13.6% and 10.2% in the NH and SH, respectively. These numbers suggest that the three additional AMSU-A instruments add resilience to the GOS, consistent with Andersson and Sato (2012). Furthermore, they suggest that an early-AM satellite, in particular, would add value and overall resilience to the GOS due to improved global data coverage over a 6-h period.

The skill distribution analysis demonstrates the well-known fact that the GFS (and any other operational forecast system) produces forecasts of variable skill from day to day. With an annual accumulation of scores to account for seasonal changes in forecast skill, it appears that the distributions are stable and well describe annual skill improvements due to scientific development and observing system changes. In particular, improvements to the GFS over almost two decades have dramatically changed the distribution of scores, and similar shifts in skill distribution are seen by removing the PM orbit observations in this OSE.

On any given day, even when the GDAS is cycled from its preceding instance, the resulting forecast may have more or less skill, depending on many factors. Some of these factors are the synoptic meteorology of that day; the accuracy of the initial analyses; the amount, type, and quality of observations; the ability of the quality control to remove erroneous observations and the ability of the observations to measure the key synoptic features; and the analysis and model accuracy for projecting the analysis forward in time. All in all, the diversity and complexity of these factors conspire to make the predictability of a single forecast from a single forecast system a challenging task, even when ensemble techniques are introduced (e.g., Wobus and Kalnay 1995; Tan and Xie 2003). The skill distribution analysis for NOPM can be quantitatively interpreted as an increased risk of producing more forecasts in the low end of the CNTL skill distribution and a reduced probability of producing forecasts at the high end.

We suggest that this skill distribution analysis could be useful for users, in particular for operational forecasters who desire and appreciate documentation on the performance of the numerical guidance used every day. Changes in the likelihood of making the worst or best forecasts (namely, on either end of the skill distribution) could be beneficial for forecaster services. In particular, quantifying a change in the risk of using guidance with an enhanced (or reduced) probability of making a comparatively better (or worse) forecast should provide decision-making information.

ACKNOWLEDGMENTS. The authors thank NCEP and the anonymous reviewers for their comments, R. Treadon for providing Fig. 2, and P. Caplan for originating the processing of GFS skill distribution. Partial support for this work was provided by the JPSS and Next Generation Global Prediction System (NGGPS) Programs via NOAA Grants 1312M41460 and NA14NES4320003, respectively.

APPENDIX A: LIST OF OBSERVING SYSTEMS USED IN NCEP OPERATIONAL GLOBAL DATA ASSIMILATION SYSTEM IN 2012–13. The GOS is an ever-changing collection of instruments and systems that provides observations to international NWP centers and also serves local government, industry, and public needs. It is important to keep track of all GOS changes in instrument type, number, quality, etc., since it is clear that operational forecast quality depends on these factors. The failure of a particular satellite instrument, for example, is only predictable statistically, as any instrument can exceed its designed lifetime or fail upon launch or soon thereafter, often with serious consequences due to the expense involved in its replacement.
Table A1 lists the types of observations, platforms, and instruments (or quantities and measurements) used operationally at NCEP during the period of this OSE.

**APPENDIX B: CONTEXT FOR OBSERVING SYSTEM IMPACTS.** It is informative to place observing system impacts, as demonstrated by OSEs, in context with the long-term skill improvements to operational global forecast systems, such as the NCEP GFS, as documented by a standard and representative score such as Z500AC. The Z500AC is a representative score since it measures the skill of forecast of high and low pressure locations and the vertically averaged atmospheric state, and furthermore it has a long history as a performance metric. Other scores (such as root-mean-square error) tend to move in tandem with Z500AC, while scores for precipitation and hurricane track and intensity are more specialized and tend to measure less representative aspects of atmospheric behavior.

Operational NWP centers are constantly improving their analysis and forecast systems. System improvements can result from scientific development of their many complex components. Development areas include but are not limited to increased quantity and quality of ingested observations from the GOS; improvements to the data assimilation and quality control algorithms and procedures; and improvements to various aspects of the forecast model, such as the representation of physical processes, increasing horizontal and vertical resolution, and increasing computational efficiency. Increased computational efficiency is important because it enables more sophisticated science to be added while maintaining the same computational cost in operations.

The average improvement rate for operational global forecast systems is approximately one day of skill per decade (Simmons and Hollingsworth 2002); that is, the average skill of today’s 5-day forecast is as good as that of a 4-day forecast produced a decade ago. The skill of the NCEP GFS has improved at the same rate, with average mean-annual increases in Z500AC of 0.007 (NH) and 0.010 (SH) as shown in Fig. B1. These increases in skill were due to the accumulated value of system improvements such as those noted above. For example, GFS horizontal resolution increases occurred in 1998 (100–70 km), 2002 (55 km), 2005 (38 km), 2010 (23 km), and 2015 (13 km), and all were enabled by operational high-performance computing (HPC) increases and enhanced computational

![Fig. B1. Annual-mean NCEP GFS 5-day Z500AC scores from 1996 to 2013 in NH (blue) and SH (red).](image1)

![Fig. B2. As in Fig. 6, but for NCEP operational GFS 5-day forecasts at 0000 UTC, compiled annually from 1996 to 2014.](image2)
efficiency. Most of these horizontal-resolution changes resulted in higher annual scores the next year in one or both hemispheres (Fig. B1), even though other system changes undoubtedly contributed.

Distributions of GFS forecast skill for each year over the period 1996–2014 (Fig. B2) provide even more information on the impact of improvements. Despite some minor year-to-year variability in forecast skill due to different weather patterns and despite the fact that GFS upgrades occurred irregularly over this period, it is generally apparent that each annual skill distribution is unique to the GFS of that particular year. Notably, as annual-mean scores have increased, their skill distributions are characterized by a reduced frequency of low scores and an increased frequency of high scores. Contrast, for example, the distributions for NH over 1997–99 and 2012–14: Scores in the range 0.525–0.625 constituted 16%–18% of the total in the earlier period but 1% in the most recent years. From 1997 to 1999, the GFS scores did not reach 0.925 but, in each year of 2012–14, 30%–35% of the NH scores did so.

As a forecast system improves its ability to extract observational information through its DAS and increase its forecast skill through a better model, it becomes more resilient to changes in the observing system and less likely to produce forecasts in the lower range of scores.

REFERENCES


A Half Century of Progress in Meteorology:
A Tribute to Richard Reed

with selections by: Lance F. Bosart  Robert W. Burpee  Anthony Hollingsworth
James R. Holton  Brian J. Hoskins  Richard S. Lindzen  John S. Perry  Erik A. Rasmussen
Adrian Simmons  Pedro Viterbo

Through a series of reviews by invited experts, this monograph pays tribute to Richard Reed’s remarkable contributions to meteorology and his leadership in the science community over the past 50 years. 2003.

AMS Code MMS3.
List price: $80.00
AMS Member price: $60.00

ORDER ONLINE: bookstore.ametsoc.org or see the order form at the back of this issue
Numerical weather prediction (NWP) is based on computer models, which describe the state of the atmosphere using mathematical equations in order to predict the evolution of weather conditions. Though attempted in the early 1900s, it was not until 1950 that the first successful weather forecast was recorded (Charney et al. 1950). This proved NWP was feasible and could produce realistic weather forecasts. The United States started to perform NWP operationally in mid-1955. The payoff came in 1958 when skillful, timely numerical predictions were delivered to forecasters to provide guidance for the then-manually prepared prognostic charts (Shuman 1989). Currently, operational NWP centers around the globe run a myriad of models. These models, some of which were developed and are run by the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS), produce a wide variety of products and services for atmospheric and oceanic parameters, hurricanes, severe weather, aviation weather, air quality, and so on. Advancement of modern NWP is due to revolutionary improvements in a number of key areas, including developments in the theory of meteorology, innovations of observational instrumentation and technology, and advancements in modern computers and their massive computing capabilities. Similarly, NWP in the United States has progressed consistently through the years and its products are being used widely around the world. However, in recent years, concerns have arisen from the research community regarding the NWP improvement rate in the United States (Mass 2012). The lack of advanced
data assimilation techniques and insufficient use of observations in operational data assimilation systems were recognized as some of the key elements.

The purpose of data assimilation in an NWP system is to provide an initial set of conditions with an optimized combination of background (e.g., the forecast from the previous cycle of the NWP model) and observation information obtained through weather stations, ships, satellites, and other observational instruments. Many previously published articles introduce the concepts and applications of data assimilation (e.g., Daley 1991; Navon et al. 1992; Houtekamer and Mitchell 1998; Wu et al. 2002; Kalnay 2003; Barker et al. 2004; Whitaker et al. 2011). Prior to 2012, the operational data assimilation system at NOAA was dominated by the three-dimensional variational data assimilation (3DVAR) technique, while other operational centers in the world had transitioned to more advanced techniques (e.g., 4DVAR for the European Centre for Medium-Range Weather Forecasts (ECMWF; Mahfouf and Rabier 2000); hybrid ensemble-variational (EnVar) technique for the Met Office (Clayton et al. 2013)). Transitioning advanced data assimilation techniques from the research community to operations and taking maximum advantage of current and future observations, especially satellite data, had become urgent and critical for improving the quality of NWP in the United States.

Over the past few decades, many efforts have been made in the research community to improve data assimilation techniques and NWP systems. Serafin et al. (2002) discussed potential avenues that would facilitate the transition of new scientific research and technology to the NWS. Among these, community-based modeling efforts were considered an important route for research to operations (R2O) transitions. The source code for these community models/systems became publicly accessible and could be updated with contributions from a broader community, including universities, operational agencies, and the private

<table>
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<th>Table 1. Conventional observations (including satellite retrievals and synthetic data) ingested into the GSI community release, version 3.4.</th>
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<tr>
<td><strong>Radiosondes</strong></td>
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<td><strong>Pilot balloon (PIBAL) winds</strong></td>
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<td><strong>Synthetic tropical cyclone winds</strong></td>
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<td><strong>Wind profilers: United States, Japan Meteorological Agency (JMA)</strong></td>
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<td><strong>Conventional, Aircraft to Satellite Data Relay (ASDAR), and Meteorological Data Collection and Reporting System (MDCRS) aircraft reports</strong></td>
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<tr>
<td><strong>Dropsonde</strong></td>
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<tr>
<td><strong>Moderate Resolution Imaging Spectroradiometer (MODIS) IR and water vapor winds</strong></td>
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<tr>
<td><strong>Geostationary Meteorological Satellites (GMS), JMA, and Meteosat cloud drift IR and visible winds</strong></td>
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<td><strong>European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and Geostationary Operational Environmental Satellite (GOES) water vapor cloud-top winds</strong></td>
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<tr>
<td><strong>Goddard Earth Observing System (GEOS) hourly IR and cloud-top wind</strong></td>
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<td><strong>Surface land observations</strong></td>
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<td><strong>Surface ship and buoy</strong></td>
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<td><strong>Special Sensor Microwave Imager (SSM/I) wind speed</strong></td>
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<tr>
<td><strong>Quick Scatterometer (QuikSCAT), the Advanced Scatterometer (ASCAT), and the Oceansat-2 Scatterometer (OSCAT) wind speed and direction</strong></td>
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<tr>
<td><strong>SSM/I and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) precipitation</strong></td>
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sector. Such examples include the Advanced Research version of the Weather Research and Forecasting (WRF) Model (ARW; Skamarock et al. 2008), the Community Radiative Transfer Model (CRTM; Han et al. 2006), the Data Assimilation Research Testbed (DART) system (Anderson et al. 2009), and the WRF Data Assimilation (WRFDA) system (Barker et al. 2012). This article provides an overview of an effort centered at the Developmental Testbed Center (DTC) to provide a “new” data assimilation system to the community. Unlike many current community models/systems originating from the research community, this community data assimilation system was transitioned from an existing operational system and continues to be run for daily weather forecasts, while remaining open to the research community. Through this effort, the DTC works closely with the developers to explore the potential to bridge the research and operational data assimilation communities and help accelerate R2O transitions. Experiences and lessons gained via this effort are discussed in this article.

HISTORY OF THE DTC AND COMMUNITY GSI EFFORTS. The DTC (Bernardet et al. 2008; Ralph et al. 2013; www.dtcenter.org/) is a distributed facility, residing at the National Center for Atmospheric Research (NCAR) and NOAA’s Earth System Research Laboratory (ESRL). The DTC collaborates with operational centers and the research community, supporting numerical models and their research, developing verification tools, and performing objective tests and evaluation of NWP methods. The WRF-Nonhydrostatic Mesoscale Model (WRF-NMM) is the first operational model for which the DTC provided support to the research community, in partnership with its development team at the National Centers for Environmental Prediction (NCEP). Since then, the DTC has further explored promoting usage of operational systems in the research community and enhancing the collaboration between the operational and research communities. For example, the DTC is currently providing full user support for the Hurricane WRF (HWRF; Bernardet et al. 2015). This article introduces the initial effort of the DTC in the area of data assimilation, providing the Gridpoint Statistical Interpolation analysis system (GSI) to the research community and building the pathway for data assimilation R2O transitions.

GSI is a state-of-the-art analysis system, initially developed by NCEP’s Environmental Modeling Center (EMC). It was designed as a traditional 3DVAR system.

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<tr>
<th>Instrument</th>
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<tr>
<td>SBUV</td>
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<td>GOES <em>IMG</em></td>
<td>GOES-11, GOES-12</td>
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<td>Atmospheric IR Sounder (AIRS)</td>
<td>Aqua</td>
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<td>MetOp-A, NOAA-18, NOAA-19, Aqua</td>
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<td>AMSU-B</td>
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<tr>
<td>SSM/I</td>
<td>Defense Meteorological Satellite Program (DMSP) F14, DMSP F15</td>
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<tr>
<td>Special Sensor Microwave Imager/Sounder (SMIS)</td>
<td>DMSP F16</td>
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<td>Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E)</td>
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<tr>
<td>Infrared Atmospheric Scanning Interferometer (IASI)</td>
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<tr>
<td>Global Ozone Monitoring Experiment (GOME)</td>
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<td>Advanced Technology Microwave Sounder (ATMS)</td>
<td>Suomi NPP</td>
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<tr>
<td>Cross-track Infrared Sounder (CrIS)</td>
<td>Suomi NPP</td>
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applied in gridpoint space to facilitate the implementation of anisotropic inhomogeneous covariances (Wu et al. 2002; Purser et al. 2003a,b). This 3DVAR system replaced NCEP’s operational grid-space regional analysis system for the North American Mesoscale Forecast System (NAM) in 2006 and the global Spectral Statistical Interpolation (SSI) analysis system for the Global Forecast System (GFS) in 2007 (Kleist et al. 2009). In the past few years, along with the community framework being built for both internal developers and the rest of the research community, GSI has evolved to include various data assimilation techniques for multiple operational applications, including 2DVAR [e.g., the Real-Time Mesoscale Analysis (RTMA) system; De Pondeca et al. (2011)], the hybrid EnVar technique [e.g., the data assimilation systems for GFS, the Rapid Refresh system (RAP), NAM, HWRF, etc.], and 4DVAR [e.g., the data assimilation system for the National Aeronautics and Space Administration’s (NASA) Goddard Earth Observing System, version 5 (GEOS-5); Zhu and Gelaro 2008; Todling and Tremolet 2008]. Currently, GSI is under development to extend its 4D data assimilation capability through inclusion of the hybrid 4D–EnVar approach (Kleist and Ide 2012) with plans to apply this technique to the upcoming GFS implementation scheduled for 2016 (Tallapragada 2015).

As for other operational models and systems, a sustained development effort is granted to GSI within the research teams that support operational applications (therefore mostly considered to be “internal” teams to operational centers). High priority is given to incorporating new observational instrument measurements, especially satellite data. A complete list of data types assimilated by the latest community release code, GSI v3.4 (released in July 2015), can be found in Tables 1 and 2. The latest information can be accessed through the community GSI user’s web page (available online at www.dtcenter.org/com-GSI/users/). Such GSI development benefits from a close relationship between data providers [e.g., the National Environmental Satellite, Data, and Information Service (NESDIS)] and operational centers. For example, it only took seven months after the Suomi National Polar-Orbiting Partnership (Suomi-NPP) satellite mission was launched for NCEP to assimilate the Advanced Technology Microwave Sounder (ATMS) data into real-time GFS operations (Collard et al. 2013). Running efficiency is another focus area of the development team for operational applications. Though the amount of ingested data is rapidly increasing, the GSI code continues to be optimized to fit into limited operational windows. In addition, GSI operational applications have created solid reference configurations and benchmarks. All these aspects provide advantages when using such an operational system for research.

While gaining popularity for operational weather forecasts as well as climate studies (e.g., GFS reanalysis), GSI was not well recognized as a research system prior to 2009 when the community GSI effort was initiated. The code was developed within an operationally driven working environment for specific computing resources (e.g., NOAA computers). Therefore, portability was one of the biggest issues when running on other computing platforms. Documentation was neither well developed nor publically available. Individual communications among developers were often the only choice available to gain access to the latest code and for development coordination. Even within the same operational center, GSI was prone to code divergence since GSI has been continuously under development for different scales and implemented along varying timelines among applications.

At the same time, data assimilation techniques were rapidly advancing in the research community, some of which were developed within the context of other available data assimilation systems and computing environments. An example is the hybrid data assimilation technique, which incorporates ensemble-based flow-dependent background error information into a variational data assimilation system (Lorenc 2003; Buehner 2005; Wang et al. 2008; Barker et al. 2012). Transferring these research advancements into the operational GSI was typically tedious and costly. Developers who were not working closely with the GSI development team found it difficult to stay abreast of the latest GSI capabilities and/or test their new advances within the operational GSI environment. These challenges led to gaps in the process of transitioning research from this distributed development effort into a single system.

Learning from other community system efforts, the DTC recognized it is critical to build a close partnership with development teams from both the research and operational communities and provide a pathway for both sides to communicate and collaborate. Meanwhile, it was also recognized that an organized effort should be sustained to provide assistance with code development and research, as well as to support real-time operational implementations at multiple operational centers. The following section describes the measures and steps taken by the DTC to unify the cross-development teams (including those internal to operational centers) and promote the usage and development of the operational data assimilation system in the general research community.
COMMUNITY GSI FRAMEWORK AND SUPPORT. Code repository. Learning from other community systems and models, both the DTC and EMC recognized that a common code repository is an effective way to provide a traceable history of the code and open code access to different types of developers, either from a research facility, the private sector, or an operational center. In 2009, EMC created a code repository using Subversion (https://subversion.apache.org/), a versioning and revision control system, to serve the purpose of in-house code management and meet the implementation requirements within NCEP. While this operational repository has made code development and sharing much more efficient between the internal developers and operational teams, this repository unfortunately resides inside the NOAA security firewall and does not meet the open-access requirement to serve external users. The DTC’s strategy for addressing this access issue was to create a parallel GSI community repository. The community repository mirrors all components residing within EMC’s GSI operational repository, while also containing files not necessarily required by internal EMC users, for example, supplemental libraries required for running GSI, multiple-platform compilation tools, simplified run scripts, community-shared diagnostic utilities, and so on. This approach provides the least intrusive option for the established operational framework. This community repository is open to all users and developers, with an application procedure in place guided by the laws of the U.S. government. The DTC provides the aforementioned additional files and online support to assist users in compiling, configuring, and running GSI using their own computing resources (usually non-NOAA computers).

Users of the GSI repository (either the operational or community repository) can check out the latest code from the repository “trunk” for further development and/or releases (e.g., GFS operational implementations and community GSI releases). All repository users can create their own branches attached to the repository trunk for active development, code testing, and bug fixes. Code divergence among developers (and branches) can be sufficiently avoided through developers committing incremental changes to the trunk and synchronizing branches with the trunk in a timely manner. The code transition from branches back to the trunk, as well as the synchronization of the community and operational repositories, are

![Diagram of GSI development transition procedure](image)

**Fig. 1.** Schematic of the GSI development transition procedure and its connection with the GSI repository. Active development is conducted in the repository branches and communicated among developers through development coordination meetings. Once a code update is ready, it will be reviewed and tested by the GRC, and then, if approved, committed to the EMC repository trunk (mirrored by the DTC repository trunk).
managed by a procedure developed and monitored by the GSI Review Committee (GRC). The following section introduces the code transition procedure and its connection to the code repository(ies) (Fig. 1).

**Code management.** The GRC is the core of the GSI code management structure. It was formed in 2010 with a goal of incorporating all major GSI development teams in the United States within a unified community framework. It was expanded in 2011 and currently includes members from EMC, the Global Modeling and Assimilation Office (GMAO), ESRL, NCAR, the U.S. Air Force (USAF), NESDIS, and the DTC (chair). As the only organization focusing on user support, the DTC takes on the role of connecting the GRC with developers whose organizations are not represented. The GRC is open to all developers for new membership application. The committee members are responsible for proposing and shepherding new code advances, coordinating ongoing and future development, and providing advisory guidance to community GSI efforts. Two sets of formal meetings are in place to facilitate communications among developers, quarterly GRC meetings hosted by the DTC, coordinating development among major development teams, and biweekly GSI developer meetings hosted by EMC, open to all individual developers for ongoing research and code updates.

Another important function of the GRC is to review code updates/advances to be committed to the code repository. The GRC members review new code developments using their own testing suites, usually associated with operational configurations. Once the GRC reaches unanimous approval for the code changes, EMC and the DTC perform final software sanity tests and commit the code changes to the GSI repository trunk (the operational and community repositories are synchronized for each code commit). Since most of the development work is originally designed for a particular application, this rigorous test–review–test mechanism ensures the GSI system is stable and robust and prevents unexpected changes to all operational applications involved in this community GSI effort.

**Community code access and support.** In addition to providing active developers with the developmental GSI system, in 2010 the DTC began providing the general research community with code access through the community GSI user’s website (www.dtcenter.org/com-GSI/users/index.php). This website provides an annual released GSI package, including supplemental libraries, fixed input files, reference configurations, the multiple-platform compilation tool, and sample run scripts, as well as diagnostic utilities. The DTC

| Table 3. Community GSI code releases and outreach events hosted by the DTC (up to 2015). |
|---------------------------------|---------------------------------|---------------------------------|
| **Public release** | **Tutorial/instructional session** | **Workshop** |
| 2009 | Version (v) 1.0 | • GSI instructional session, 10th WRF Workshop, Boulder, Colorado |
| | | • Introduction to GSI, WRF Data Assimilation (WRFDA) system tutorial, Boulder, Colorado |
| 2010 | v2.0 | GSI tutorial, Boulder, Colorado |
| | v2.5 | |
| 2011 | v3.0 | • GSI tutorial, Boulder, Colorado |
| | | First Community GSI Workshop, Boulder, Colorado |
| | | • BUFR/PrepBUFR<sup>a</sup> tutorial, Boulder, Colorado (with remote access) |
| | | GSI–Hybrid Workshop, Miami, Florida (with remote access) |
| 2012 | v3.1 | GSI tutorial, Boulder, Colorado |
| 2013 | v3.2 | • GSI tutorial,<sup>b</sup> College Park, Maryland |
| | | • GSI instructional session,<sup>c</sup> Beijing, China |
| | | Second Community GSI Workshop,<sup>b</sup> College Park, Maryland (with remote access) |
| 2014 | v3.3 | GSI tutorial, Boulder, Colorado |
| 2015 | v3.4 | GSI/EnKF tutorial, Boulder, Colorado |

<sup>a</sup> Binary Universal Form for the Representation of Meteorological Data (BUFR) is the data format used by GSI. PrepBUFR is the NCEP-tailored BUFR file format for conventional data.

<sup>b</sup> Jointly hosted by EMC and the Joint Center for Satellite Data Assimilation (JCSDA) at NOAA’s Center for Weather and Climate Prediction (NCWCP).

<sup>c</sup> Session held at the invitation of the Beijing Urban Meteorology Institute.
composed the first GSI user’s guide in 2009, in collaboration with developers, and has since provided updated documentation along with annual releases. The website also provides online exercises, test cases, and other GSI information.

To assist GSI users and developers, the DTC provides training and online support, following each code release. Both fundamental and advanced GSI topics are covered during the tutorials to meet the various needs of GSI users. Users can also practice GSI by completing the hands-on tutorial sessions. The DTC also periodically hosts GSI workshops to promote data assimilation research, which enhances the connections between the operational centers and community researchers. Past GSI community events are listed in Table 3. All of the presentations from these events can be accessed through the GSI community website.

The DTC Visitor Program is another important mechanism the DTC offers to promote the use of operational capabilities in the research community and to assist with transferring research advances to operations. This program provides financial and computing resources for projects that are usually associated with the operational systems supported by the DTC and have been through a rigorous review process. A list of GSI and associated data assimilation visitor projects (including the final reports) can be found online (www.dtcenter.org/visitors/data_assim/).

**GSI code tests.** During the transfer of the operational GSI to a unified community system shared with distributed developers and users, it was recognized that performing standard and centralized code tests is essential to avoiding intrusive damage to the incorporated GSI operations and maintaining the integrity and robustness of GSI. The DTC works closely with the GRC members to build a solid testing and evaluation procedure for GSI. Currently, three types of regular tests are in place for GSI maintenance: repository regression tests, preimplementation tests, and the DTC community code tests.

**Regression tests.** Running regression tests is an essential part of the code review procedure and repository maintenance. The suite of regression tests contains a set of preconfigured cases to be run prior to and after new code is committed. These cases are selected to test certain components or configurations of GSI (e.g., running GSI in the global domain or for a tropical storm case). The size of the cases is usually small so that they can be run within a short time frame. The regression tests are performed for each update to the code repository trunk and the results provide information on whether, and how much, the computational cost and scientific performance have changed because of the particular update. Current regression tests, managed by both the DTC and EMC, are designed to run multiple reference configurations associated with operational applications (GFS, HWRF, RTMA, etc.) on multiple platforms. Running these regression tests has proven to be sufficient in preventing most system crashes stemming from new development. Many of the code issues, especially those related to portability and compatibility, are tackled through regression tests during the code review procedure before changes are added to the GSI trunk. The regression tests are updated periodically based on developers’ input.

**Preimplementation tests.** Preimplementation tests refer to those tests performed inside operational centers prior to a particular operational implementation. A general practice is for an operational center to conduct an extensive period of real-time parallel runs using updated GSI capabilities, compare the generated results with the then-operational products, and evaluate the code robustness and impacts of the new add-ons. Though this type of testing may sound irrelevant to general researchers, the preimplementation tests play an important role in ensuring that the GSI code remains solid and robust. Since parallel runs are usually performed for multiple months, seasons, or even years depending on the requirement of the particular application implementation, GSI is tested continuously and thoroughly for those operational configurations.

**Community test bed.** Preimplementation tests are essential for operational implementations to evaluate research and code advances before they are transitioned to operations. However, they are usually not available to external users and developers. Therefore, the DTC strived to build a community GSI test bed. Through such a test bed, researchers can evaluate new development impacts in a near-operational environment and, therefore, testing results are more relevant for the implementation of decision-making processes at operational centers. This test bed is an end-to-end system that includes preprocessing, GSI, the forecast model (e.g., ARW, NMM, HWRF, etc.), postprocessing, and verification, as well as archived operational datasets and other input files. In consultation with operational agencies, this test bed can be set up to be functionally similar to a particular operational configuration. The DTC testing capabilities are open to researchers through the DTC Visitor Program. Internally, the DTC uses this test bed for community release tests and tutorial practical sessions. The test
A majority of the past attendance for the previous GSI tutorials. Over 50% of the United States and the international community in the code repositories), with over 300 individuals from the DTC GSI website (in addition to the users using also significantly increased since 2009. Currently, there are over 1,000 community users registered through the community GSI framework. The direct result is the rapid advancement of GSI. Since 2009, GSI has evolved into a data assimilation system containing advanced data assimilation techniques (e.g., hybrid EnVar), with better usage of observational measurements (e.g., cloudy radiance). The GSI code itself is more modular and modernized, as well as becoming portable and easier to edit for developers. Through many factors contributing to the GSI evolution (e.g., strong support of operational centers), this community GSI effort has helped stimulate more coordinated development and closer communication inside the development teams and among distributed developers. For example, before the code management procedure was implemented, the initial cloud analysis capability, currently included in GSI, developed by ESRL and the University of Oklahoma (Hu and Xue 2007; Hu et al. 2008), took more than a year to be accepted into the operational GSI for many reasons (e.g., code divergence, inconsistent coding standard, lack of development coordination). Transferring this research capability to operations was the first working case to which the GRC applied the code management procedure. The functions of the GRC and the code management framework were finalized during this process. As a result, over the past five years, the GRC has received about 100 code review requests, each with multiple code changes. One such request usually takes approximately five business days for a code review and one business day for the code to be committed to the GSI trunk. Currently, all of the GSI implementations in the U.S. operational centers, as well as the DTC community releases, come from the GSI repository managed within this community GSI framework.

Usage of GSI in the general research community has also significantly increased since 2009. Currently, there are over 1,000 community users registered through the DTC GSI website (in addition to the users using the code repositories), with over 300 individuals from the United States and the international community in attendance for the previous GSI tutorials. Over 50% of the current GSI registered users come from the university community. Incorporating the research community with operational center developers has broadened the scope of GSI development and research. In 2012, GSI implemented the hybrid DA technique, resulting in significant improvement in the GFS forecast score. This implementation resulted from a great collaboration among developers from multiple groups, including EMC, ESRL, and the University of Oklahoma. Research within this area took place independently by Whitaker et al. (2011), Kleist and Ide (2012), and Wang et al. (2013). Through the developer meetings, working areas were identified among these researchers and the hybrid capability was implemented into GSI through merging the code contributions from each contributor. Another community contribution example is the addition of the aerosol optional depth (AOD) assimilation capability. This capability was initially developed by Liu et al. (2011) at NCAR and transitioned to the operational GSI code with the assistance of the DTC. This capability was made available through the 2011 annual GSI release. Currently, this capability is being further developed by GMAO and ESRL.

DTC code tests for operations. A majority of the past DTC GSI testing and evaluation activities have been conducted for regions outside the North American domain, where most of the operational GSI tests in the United States are performed. To help with operational implementations, the DTC tests alternative data types or configurations (system setup, parameter tuning, etc.) and provides suggestions and feedback for the preimplementation parallel tests performed at the operational centers. Such testing components can be either developmental capabilities from the research community or existing capabilities, which are not yet adopted by a particular application.

To help explain how the DTC tests assist in the operational implementation of GSI, including system tuning and testing, an example of DTC code tests performed for the USAF mesoscale applications is shown in Fig. 2. This test was performed to evaluate three different prescribed static background error (BE) statistics for one of the USAF’s regional domains. The motivation of this test comes from the requirement of USAF operations to run GSI in many regional domains throughout the world with a strict time constraint. Given the domain locations, the dimensions and resolutions may be altered as necessary, making the background errors a priori critical. The DTC was tasked with helping select one of the three prescribed BE files generated originally by NOAA for GFS, NAM, and RAP. The GFS and NAM BE files are also included in
the annual GSI release packages. The testing was performed across a Northern Hemisphere domain. The BE forecast impact was monitored in a series of real-time and retrospective runs. Figure 2 shows the general operations (GO) indices for the GSI runs using different BE statistics during one of the retrospective testing periods. The GO index number is a ratio used for decision-making purposes by the USAF. It is composed of a series of skill scores, weighted by lead time, for wind speed, temperature, dewpoint temperature, heights at various levels and the surface, and mean sea level pressure. Given this definition, values of the GO index that are less than one indicate the control configuration has lower forecast skill and values greater than one indicate that the test configuration has higher forecast skill. Results in Fig. 2 show that the most positive impact on the forecast skill comes from the NAM BE, for which the GO index is larger than 1 for most of the testing period. Note the sensitivity of analyses and forecasts to BE is variable dependent and therefore decisions should be made based on the application specifics. For this study, the GO index is set up with higher weighting on USAF-selected variables (e.g., wind). Figure 3 shows the root-mean-square errors (RMSEs) of wind and temperature at the analysis time for each of the BE runs. Using the NAM BE significantly reduced the wind analysis error between 700 and 200 hPa. However, it generated larger temperature analysis errors compared with the run using the GFS BE. So the higher forecast skill results from NAM shown in Fig. 2 benefit at least in part from the improved wind field analyses. In addition to the three available operational BE files, a domain and model-specific BE file can also be generated using a background error generation tool developed at NCAR (Descombes et al. 2015). The DTC tested this community capability for the USAF as well. However, the GSI analyses and forecasts generated using this particular BE set were not superior to those of the NAM BE run. Based on results from these short-term experiments performed by the DTC, the tested configurations were fed into the USAF real-time parallel experiments, which were then compared to the production runs. Following the DTC’s recommendation, the GSI runs continuously outperformed the production runs in a month-long test, as shown by Martinelli (2013).

Data sensitivity studies are another common area of work that utilizes the DTC test bed. One of the tests the DTC conducted in 2014 was to evaluate the impact of the Solar Backscatter Ultraviolet/2 (SBUV/2) profile ozone data in the USAF GSI and ARW systems. The DTC performed this test to help the USAF determine whether the SBUV/2 data, as an additional data type for assimilation, might improve the weather forecasts. Figure 4 shows the time series of temperature RMSEs at 50 and 500 hPa with and without the SBUV/2 ozone assimilated for 1–31 August 2014 across an eastern North Pacific domain. Note that ozone is not a prognostic variable in ARW and, therefore, the impact of ozone data assimilation was expected to diminish with time. However, it is clear that the positive impacts on the temperature forecasts are significant throughout the first 48 h. Similar positive impacts were also present for the wind forecasts. This outcome suggests a promising application of ozone data assimilation for regional weather forecasts. The configured GSI system and the testing results were reported to the USAF and will be considered for operations.

The previous two examples demonstrate the types of tests the DTC performs for our operational sponsors.
Many of these tests were performed in a functionally similar environment with real-time or retrospective operational cases. Therefore, the testing results were directly adopted by the specific operational centers for their implementation decision process. The operational centers then combined the suggested configurations (tuned parameters, selected observation types, etc.) with other updates and performed longer-term preimplementation tests for a final decision. More diagnostics and analyses are performed as part of these DTC tests and the results are included in the DTC reports for the sponsors. The DTC posts these reports on the DTC testing and evaluation website (www.dtcenter.org/eval/data_assim/) and also presents the results to the research community through DTC community outreach events, conferences, and meetings.

Lessons and potential directions. Though the community GSI effort has made significant progress in the past few years, improvements upon current efforts are still needed (e.g., merging operational and community repositories), while a number of challenges still remain. Most of, if not all, the GSI development comes from the major development teams already incorporated in the GRC. Contributions from the rest of the research community are limited and many reasons may contribute to this issue. First, compared with the modeling community, the data assimilation research community is relatively small and the number of developers of GSI is even smaller. Applications to the DTC Visitor Program in the data assimilation area are also limited, in comparison with other areas (e.g., model physics or verification). However, it is evident that there is more organized GSI usage in the United States and throughout the international community, with increasing GSI-related presentations and papers appearing at conferences and workshops. This implies the promotion of GSI in the research community is working and many users have gone through the learning curve and have begun real development and research efforts. Therefore, it is essential to continue with the GSI outreach events and community support to sustain community interest. Second, the research community lacks incentives to contribute back to the operational systems. Currently, it is up to the researchers to come forward with feedback to GSI development. In addition, even in cases where some community researchers have agreed to contribute back to the operational code, performing objective and independent code tests was not always feasible. Sometimes, the developmental code, which has been evolving continuously, has not been available for the DTC to perform testing over an extended period or researchers were not willing to share their research code.

Now, since the pathway from research to operations has been laid out and proven to be working properly, it is time to seek more sufficient measures to encourage the involvement of the general research community in operational data assimilation development. The success of the NOAA Hurricane Forecast Improvement Program (HFIP; www.hfip.org/) and the latest Next Generation Global Prediction System program (NGGPS; www.nws.noaa.gov/ost/nggps/) might provide ideas for the community GSI effort and similar community modeling efforts. These two programs were initiated within the operational community, enticing the research community to directly contribute to the development of operational models/systems. However, only when appropriate code management framework and code transition procedures (including tests and reviews) are incorporated through

![Fig. 3. RMSEs of (left) wind and (right) temperature analyses from NAM (green), RAP (red), and GFS (blue) BE runs. The analyses were verified against conventional observations. The horizontal bars show the errors at the 95% statistical significance level.](image-url)
the projects of such a program, will the transition from research to operations be efficient and smooth. It seems reasonable that a close collaboration between the DTC and such a program may direct community efforts to more motivated developers for R2O.

Second, it has been noted that maintaining GSI capabilities or adding new capabilities might become difficult when the associated development efforts are not sustained for some reasons. The DTC is not a development center and, therefore, it is not straightforward to gain expertise in research development without direct involvement from the developers. For example, the DTC was working with NCAR to transition the ARW-based GSI 4DVAR capabilities (Zhang and Huang 2013) to the community code. However, this work cannot be completed since there were no additional resources for NCAR to update the adjoint model for each release of GSI and ARW, which is, however, mandatory for releasing the 4DVAR capabilities to the public.

The third issue is also associated with the rapid development of GSI. GSI has interfaces with both global and regional models and incorporates many different types of observational instruments (some might have been discontinued). The GSI code is showing a trend toward becoming a “giant” eventually if no constraint is put in place for distributed contributions. This is also a common issue many community models may eventually confront. An over-sized system is not desired from an operational viewpoint, since its operational efficiency might be in jeopardy and its maintenance may become difficult over time. Meanwhile, the research community prefers flexibility and more run-time options (other data and background formats, different parameter tuning and configuring, etc.) with which to perform research and make improvements. How to meet this twofold need is a question for the community GSI effort and many other similar community efforts.

An intermediate solution to the last two issues is to modernize the existing system, GSI in this case. Recently, there have been discussions within the GRC and among other collaborators related to the possibility of refactoring GSI. The GSI code may be decomposed into multiple libraries/modules/components, with the flexibility to plug in and out. By doing so, obsolete capabilities can be safely removed and new capabilities or updates can be implemented more easily. The interface of data and background files to GSI may be handled externally to save memory and computer time. The observation operators, which transfer model state variables to observational space, can also become relatively independent of the solver of the GSI and therefore more easily adopted by other data assimilation systems (e.g., by an ensemble-based data assimilation system) or for verification purposes (e.g., verification against nontraditional satellite observations). Currently, there are existing tools available to the modeling community that provide such a modeling framework, for example, the Earth System Modeling Framework (ESMF; www.earthsystemcog.org/projects/esmf). The NOAA Environmental Modeling System (NEMS) is based on ESMF in an effort to streamline the components of operational modeling suites at NCEP. GSI, or similar community efforts, would certainly benefit from a similar effort, within the code management framework. Another possibility is to invest in next-generation data

Fig. 4. Time series of temperature RMSEs from the control (blue) and SBUV runs (green, including data from the control experiment plus the SBUV ozone) at (left) 50 and (right) 500 hPa. The black dashed line indicates the pairwise difference. The difference is statistically significant if the confidence intervals do not encompass zero. Statistical significance is determined at the 99% level.
assimilation. The code management and transition framework should be considered from the beginning, while designing such a system. Developers would be required to receive education on building such a system with certain coding standards and requirements so that the code would be more modularized and modernized. Desired capabilities should be included, as well as the preferred interface for portability and interface flexibility.

Last, but not least, is the issue of the community GSI effort being actually beyond the GSI system itself. A data assimilation system is linked to data preprocessing, forecast models, postprocessing, and verification. Currently, the DTC is providing support to all of these components except for data preprocessing. The observations available to the public are sparse and their formats are not unified and therefore they require additional processing before being fed into GSI. Moreover, NCEP feeds GSI with quality controlled conventional data, through a preprocessing process. This process is not available through the existing community framework. Without access to near-operational datasets and appropriate quality control, research efforts using GSI might not be relevant enough to operations. Providing support for the data preprocessing process might be the next step in helping to complete this community GSI effort.

SUMMARY AND FUTURE PLANS. Starting in 2009, a joint effort between the DTC and NCEP/EMC was initiated to expand the operational GSI data assimilation system to the research community, with the sponsorship of NOAA, the USAF, and NCAR [supported by National Science Foundation (NSF)]. The objectives of this effort are to provide operational capabilities to the research community, open up pathways for the research community to contribute directly to daily operations, and, eventually, accelerate transitions from research to operations, which is in line with the mission of the sponsors and the DTC.

This effort has produced a code management framework capable of unifying the distributed development and operational applications. Major GSI development teams across the United States are members of the GSI Review Committee, which is tasked with coordinating and reviewing code development. The GSI system and its supplemental libraries and auxiliary files are managed in the GSI Community Repository under version control (using Subversion). Targeted code tests are organized to maintain code robustness and integrity. General GSI community support is provided through the DTC, including code access, documentation, tutorials, a helpdesk, and assistance with code transitions and tests. Community researchers and users are encouraged to collaborate with the DTC and/or any of the GSI developers to further advance GSI and associated data assimilation techniques, following the same code management procedures as internal developers.

The close collaboration between the DTC and other primary GSI development teams (including EMC, GMAO, etc.) is critical to this community effort. This helps the DTC to better understand the needs of both the research and operational communities. It also promotes active communication about GSI development among distributed teams and enables the unified code management framework to function as expected. The framework set up during this effort, including the code management and code transition procedures, was also shared with other community efforts at the DTC.

However, through this community effort, the DTC and its collaborators also recognized additional challenges, including issues related to discontinued development, lack of incentives for the community contributions, lack of access to data handling, and so on. The DTC continues to work with its partners to seek solutions to these issues. It might be necessary to expand the current community GSI effort to refactor this data assimilation system or get involved with the development of a next-generation data assimilation system, as well as provide support for data preprocessing. It is also necessary for the DTC to continue to expand its expertise in data assimilation and build a sufficient mechanism (with proper incentives) for motivating contributions from the research community (e.g., developers considered to be “external” to the GRC members). All these potential solutions will require even closer collaborations with operational centers and funding agencies. The DTC also welcomes comments and feedback from the research community.

Meanwhile, the DTC will continue to provide operational data assimilation capabilities to the research community. In addition to GSI, the DTC is working to provide the research community with an ensemble-based data assimilation system, the ensemble Kalman filter (EnKF) system originally developed by NOAA. This system will complement the GSI-based hybrid capabilities through a continuous update of the ensemble pieces. By the time this article is published, this EnKF system will have been released to the research community together with GSI. The DTC will continue its efforts to facilitate the research community contributions back to operations and, eventually, improve numerical weather prediction through data assimilation. It is also important for the
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REFERENCES


Soil moisture is an important state variable in the climate system, as it stimulates land–atmosphere interactions by modifying energy and wetness fluxes in the boundary layer (Legates et al. 2011). Soil water content influences evapotranspiration and corresponding near-surface atmospheric moisture availability (Pal and Eltahir 2001). Dry soil can induce and amplify warm and dry conditions, especially during the summer, by reducing local evaporation and modifying patterns of moisture convergence/divergence (Namias 1991). Soil moisture has been connected with the partitioning of surface energy fluxes (Dirmeyer et al. 2000; Guo and Dirmeyer 2013), near-surface atmospheric temperature (Hirschi et al. 2011; Teuling et al. 2010), planetary boundary layer instability (Myoung and Nielsen-Gammon 2010; Gentine et al. 2013), and the onset and location of afternoon convective precipitation (Findell et al. 2011; Taylor et al. 2012). Soil moisture is used for drought monitoring and in drought early warning systems in Asia (Wang et al. 2011; Tei et al. 2013), Africa (Anderson et al. 2012; Yuan et al. 2013), Australia (Cai et al. 2009), Europe (Zampieri et al. 2009; Mozny et al. 2012), North America (Tang and Piechota 2009; Bolten et al. 2010), and South America (Markewitz et al. 2010). However, despite the importance of soil moisture and its utility for drought monitoring, there are relatively few in situ soil moisture observations, especially in comparison to precipitation and temperature observations.

The lack of in situ soil moisture measurements means that most studies of the interactions between soil moisture and the atmosphere, biosphere, and hydrosphere are based on models. For example, Schubert et al. (2004) investigated the causes of droughts in the United States Great Plains using a general circulation model forced with observed SSTs and found that approximately two-thirds of the low-frequency rainfall variability can be explained by

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land–atmosphere interactions (e.g., soil moisture), while the remaining variance can be attributed to SST anomalies. In contrast, an observation-based study by Findell and Eltahir (1997) attributed only ~16% of the variance in summer precipitation to spring soil moisture conditions. Without accurate in situ soil moisture measurements, such discrepancies remain unresolved. GCMs have also been used to investigate soil moisture–climate interactions. The Global Land–Atmosphere Coupling Experiment (GLACE) used a 12-GCM ensemble to identify regions with strong soil moisture–climate (Koster et al. 2004, 2006). They found significant variations in the coupling strength amongst the GCMs and therefore multimodel ensembles are commonly used to study land–atmosphere interactions. Given the difficulty that GCMs and land surface models have in accurately simulating soil moisture, observed soil moisture (either in situ or satellite) is commonly used to initialize or constrain, through data assimilation, these models (e.g., Harrison et al. 2012; Kumar et al. 2012).

Soil moisture observations are also important for the validation of satellite soil moisture retrievals from missions such as the Soil Moisture Ocean Salinity (SMOS) satellite. Al Bitar et al. (2012) evaluated SMOS soil moisture estimates with in situ soil moisture observations from Soil Climate Network (SCAN) and Snowpack Telemetry (SNOTEL) observation networks in several regions of the United States. Their results demonstrated that the accuracy of SMOS-derived soil moisture varied significantly from site to site, necessitating the validation of satellite-derived soil moisture in a variety of regions. Collov et al. (2012) evaluated the accuracy of SMOS-derived soil moisture with in situ measurements in the United States Great Plains. They concluded that the lack of uniform soil moisture measurements makes evaluating SMOS difficult and therefore additional stations are needed to provide a more robust evaluation of satellite-derived soil moisture. Of course, it should be noted that there are significant scaling issues involved in comparing in situ soil moisture measurements (a point) to satellite-derived soil moisture (50-km pixel) and most in situ networks are not sufficiently dense to adequately resolve soil moisture variability within each satellite pixel.

Despite the importance of soil moisture in the climate system, relatively little work has been done to assemble and homogenize in situ soil moisture measurements and to utilize these measurements for investigating land–atmosphere interactions. Robock et al. (2000) developed the Global Soil Moisture Data Bank, providing soil moisture observations from 25 stations in the United States. The Global Soil Moisture Data Bank has since been incorporated into the International Soil Moisture Network (ISMN, www.ipft.tuwien.ac.at/insitu). ISMN is a global database of in situ soil moisture observations, containing data from 47 networks and more than 1,900 stations located in North America, Europe, Asia, and Australia (Dorigo et al. 2011).

Development of the North American Soil Moisture Database (NASMD, http://soilmoisture.tamu.edu/) began in 2011 with funding from the National Science Foundation to support the study of land–atmosphere interactions. The NASMD was developed to provide harmonized and quality-controlled soil moisture data for scientists and decision makers. For example, these data have utility for 1) improving our understanding of land–atmosphere interactions (Ford et al. 2014b, 2015a,b); 2) developing seasonal to decadal climate forecasting tools (Ford and Quiring 2013, 2014a); 3) calibrating, validating, and improving the physical parameterizations in regional and global land surface models (Xia et al. 2015a,b); 4) developing and validating satellite-derived soil moisture algorithms (Ford et al. 2014a); and 5) monitoring and detecting climate variability and change in this key hydrological variable (Khong et al. 2015).

Although ISMN and NASMD are similar in that their primary purpose is to aggregate, quality control, and disseminate soil moisture measurements, there are a number of important differences. The first is geographic focus; ISMN is a global database, while NASMD is focused on North America. A second difference is station density. The goal of the NASMD was to develop the densest possible network of in situ soil moisture in North America. A great deal of time was invested in uncovering soil moisture networks and datasets that had not been previously published or utilized in land–atmosphere studies. In some cases this involved digitizing soil moisture data that were only previously available in hardcopy (e.g., Khong et al. 2015). The NASMD has integrated data from 33 observation networks and two shorter-term soil moisture monitoring campaigns comprising over 1,800 observation sites in the United States, Canada, and Mexico. Although the NASMD includes data from some of the same networks as ISMN, it includes many networks that are not part of ISMN and so NASMD has approximately twice as many stations in North America as ISMN. A third difference between the two databases is that NASMD was initially designed to be a retrospective database for studying land–atmosphere interactions. ISMN was developed to support satellite calibration and validation activities for SMOS and it...
supports near-real-time updates (Dorigo et al. 2011). Finally, observations from networks measuring soil moisture at subdaily scales are aggregated to a daily resolution in the NASMD, while ISMN provides hourly data. Both NASMD and ISMN are heterogeneous in terms of measurement technique, measurement depth, spatial extent, and degree of automation. In addition, both ISMN and NASMD apply automated quality control algorithms to the all of the soil moisture measurements they receive.

Much of our understanding of land–atmosphere interactions has been informed by land surface and regional climate models; however, these models are difficult to validate because of the lack of observations. Soil moisture databases, like NASMD and ISMN, provide data for validation of land surface model output (Zhang and Wegehenkel 2006; Jiang et al. 2009; Meng and Quiring 2010; Tang et al. 2012) and satellite soil moisture retrievals (Jackson et al. 2012; Al Bitar et al. 2012; Rowlandson et al. 2012; Collow et al. 2012). Therefore, soil moisture databases are important for increasing our understanding of the climate system. This paper describes how development of the NASMD, including quality control/quality assurance, standardization, and collection of metadata. The utility of the NASMD is demonstrated through an analysis of the inter- and intraannual variability of soil moisture from multiple networks, and we conclude the article by highlighting some new developments and soil moisture products.

NASMD DATA. Soil moisture data sources. The NASMD has integrated data from 33 observation networks and two shorter-term soil moisture monitoring campaigns comprising over 1,800 observation sites in the United States and Canada (Table 1). Several other networks, representing over 500 observation sites in the United States, Canada, and Mexico, have agreed to contribute data in the near future. Figure 1 shows the location of sites currently available in the NASMD (soilmoisture.tamu.edu). Once we receive data from all of the networks that have agreed to provide it, the NASMD will have sites in all 50 states and six Canadian provinces, covering a wide range of soil texture, land cover, elevation, and climate conditions. The NASMD is currently the largest collection of in

<table>
<thead>
<tr>
<th>Network</th>
<th>Stations</th>
<th>Start year</th>
<th>End year</th>
<th>Measurement depths (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oklahoma Mesonet</td>
<td>129</td>
<td>1998</td>
<td>Present</td>
<td>5, 25, 60, 75</td>
</tr>
<tr>
<td>West Texas Mesonet</td>
<td>59</td>
<td>2002</td>
<td>Present</td>
<td>5, 20, 60, 75</td>
</tr>
<tr>
<td>Soil Climate Analysis Network</td>
<td>190</td>
<td>1994</td>
<td>Present</td>
<td>5, 10, 20, 50, 100</td>
</tr>
<tr>
<td>Nebraska Automated Weather Data Network</td>
<td>52</td>
<td>2006</td>
<td>Present</td>
<td>10, 25, 50, 100</td>
</tr>
<tr>
<td>Atmospheric Radiation Measurement</td>
<td>17</td>
<td>1996</td>
<td>Present</td>
<td>5, 15, 25, 35, 60, 85, 125, 175</td>
</tr>
<tr>
<td>Climate Reference Network</td>
<td>114</td>
<td>2009</td>
<td>Present</td>
<td>5, 10, 20, 50, 100</td>
</tr>
<tr>
<td>Cosmic Ray Soil Moisture Observing System</td>
<td>54</td>
<td>2008</td>
<td>Present</td>
<td>Varies (10–30)</td>
</tr>
<tr>
<td>Illinois Climate Network</td>
<td>19</td>
<td>2004</td>
<td>Present</td>
<td>5, 10, 20, 50, 100, 150</td>
</tr>
<tr>
<td>Delaware Environmental Observing System</td>
<td>26</td>
<td>2005</td>
<td>Present</td>
<td>5</td>
</tr>
<tr>
<td>NOAA Hydrometeorological Testbed</td>
<td>25</td>
<td>2004</td>
<td>Present</td>
<td>Varies (5–100)</td>
</tr>
<tr>
<td>Plate Boundary Observatory to Study the Water Cycle</td>
<td>97</td>
<td>2011</td>
<td>Present</td>
<td>2.5</td>
</tr>
<tr>
<td>AmeriFlux</td>
<td>60</td>
<td>1996</td>
<td>Present</td>
<td>Varies (5–200)</td>
</tr>
<tr>
<td>Snowpack Telemetry</td>
<td>352</td>
<td>1994</td>
<td>Present</td>
<td>5, 20, 50, 100</td>
</tr>
<tr>
<td>North Carolina ECONet</td>
<td>36</td>
<td>1999</td>
<td>Present</td>
<td>20</td>
</tr>
<tr>
<td>Alberta Agriculture and Rural Development</td>
<td>28</td>
<td>2003</td>
<td>Present</td>
<td>5, 20, 50, 100</td>
</tr>
<tr>
<td>Enviro-Weather Michigan</td>
<td>80</td>
<td>1999</td>
<td>Present</td>
<td>4, 10</td>
</tr>
<tr>
<td>South Dakota Automated Weather Network</td>
<td>11</td>
<td>2001</td>
<td>Present</td>
<td>5, 10, 20, 50, 100</td>
</tr>
<tr>
<td>Water and Environmental Research Center</td>
<td>19</td>
<td>1998</td>
<td>2012</td>
<td>Varies (5–50)</td>
</tr>
<tr>
<td>Missouri Agricultural Electronic Bulletin Board</td>
<td>31</td>
<td>2001</td>
<td>Present</td>
<td>5</td>
</tr>
<tr>
<td>FluxNet Canada</td>
<td>21</td>
<td>1998</td>
<td>Present</td>
<td>Varies (2.5–150)</td>
</tr>
<tr>
<td>University of South Alabama CHILI Mesonet</td>
<td>25</td>
<td>2006</td>
<td>Present</td>
<td>100</td>
</tr>
</tbody>
</table>
situ soil moisture observations in North America and there are >8 million observations in the database.

**Metadata.** Metadata have been collected for each site, including location, county, state, parent observation network, depths at which soil moisture are measured, type of soil moisture sensor, and the sampling frequency. In addition, soil characteristics such as bulk density, texture, percent sand/silt/clay, and hydraulic conductivity are reported at each depth that soil moisture is measured. Soil texture information from site-specific soil surveys are available for just over 1,000 of the stations included in the NASMD (~69% of all of the stations). Soil characteristics for the remaining sites are obtained from the National Cooperative Soil Survey (NRCS) Soil Survey Geographic Database (SSURGO).

The NASMD uses the land cover classification scheme provided by the Environmental Protection Agency’s National Land Cover Dataset (NLCD) 2001 ([www.epa.gov/mrlc/classification.html](http://www.epa.gov/mrlc/classification.html)) to identify the land cover at each site. If land cover information is reported by the parent observation network, it is used to identify the relevant land cover type in the NLCD classification system. Approximately 500 sites (approximately 36% of NASMD sites) provide land use and land cover (LULC) information. For the remaining sites, LULC has determined by NASDM staff using either site photos or using high-resolution satellite imagery such as Google Earth. Table 2 lists all of the parameters reported in the NASMD metadata as well as the metadata sources.

If information on soil characteristics were not collected at the site, these parameters were estimated from the United States Department of Agriculture’s SSURGO database (Reybold and TeSelle 1989). SSURGO provides soil texture and hydraulic parameter information at multiple column depths for the entire contiguous United States. In addition, Leib et al. (2003) evaluated several different soil moisture sensor estimates under alfalfa crop and showed that although the sensor trends were similar, the magnitudes of sensor estimates varied considerably. The authors concluded that sensor-specific calibration is necessary to obtain a high degree of soil-moisture-estimation accuracy. Thus, sensor change or recalibration dates are included in the NASMD metadata if these were available from the observation network.

**Data integration and harmonization.** Soil moisture observation networks use many different types of sensors to measure soil wetness. The NASMD reports all data as volumetric soil water content \( q \), which represents the ratio of the volume of water in a given soil column to the total soil column volume. Here \( q \) is influenced significantly by site-specific characteristics such as soil texture and land cover and thus should not be directly compared across space. Many of the networks that have been incorporated into the NASMD measure soil wetness at subhourly to daily time scales. However, all of the soil moisture observations in the NASMD have been resampled to daily resolution because our goal is to provide a harmonized soil moisture dataset (i.e., harmonized with respect to measurement units, time step, metadata, and QC procedures) to support a variety of applications. Resampling all the data to daily resolution results in a loss of information and it may not be ideal for all applications. For example, Ford et al. (2015a) uses soil moisture data from the morning to examine whether afternoon convective precipitation occurs preferentially over wet or dry soils. Their...
study would not have been possible with daily data. However, for many applications such as drought monitoring and model/satellite validation, daily data are appropriate and, in many cases, preferable.

Figure 2 illustrates the NASMD data processing procedure. First, raw data from all observation networks are ingested and, if necessary, data are converted to $q$ and resampled to daily resolution. All data that are provided to the NASMD are evaluated by our quality control (QC) algorithm to identify dubious or questionable values. These values are flagged and/or removed from the dataset. Small gaps (<10 days) in the data are then filled using the procedure described in Ford and Quiring (2014b) and the data (and flags) are stored in the network database (Fig. 3). Users are able to access all of the quality-controlled data for each station as well as the station metadata through the web interface (soilmoisture.tamu.edu).

**QAQC ALGORITHM.** Quality control procedures are commonly applied to a wide variety of climate and environmental datasets such as air temperature and precipitation (Hubbard et al. 2005), solar radiation (Journée and Bertrand 2011), sea surface temperatures (Merchant et al. 2008), and ocean salinity (Ingleby and Huddleston 2007); however, considerably fewer have focused on quality control of in situ soil moisture (Illston et al. 2008; You et al. 2010; Dorigo et al. 2013).

Soil moisture is one of the most difficult variables to validate with quality assurance tests because it is influenced by multiple meteorological variables and the physical and chemical properties of the soil (Fiebrich et al. 2010). Thus, a robust quality control procedure for soil moisture must include multiple, complementary data flagging techniques to assess both the magnitude and variability of the soil moisture data. Quality control algorithms are employed by a number of soil moisture monitoring networks. For example, the West Texas Mesonet’s QC method includes tests for absolute magnitude, measurement-to-measurement variability, observation persistence, and spatial coherence (Schroeder et al. 2005) and similar quality control algorithms are also used by the Oklahoma Mesonet (Shafer et al. 2000; McPherson et al. 2007) and the Nebraska Automated Weather Data Network (AWDN; Hubbard et al. 2005).

It is reasonable to ask whether it is necessary for the NASMD to develop a separate QC procedure for soil moisture. Table 2 lists the observation site properties that are included in the NASMD metadata as well as the unit and source of each parameter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network name</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>Station name</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>City</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>County</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>State</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>Latitude</td>
<td>Decimal degrees</td>
<td>Observation network</td>
</tr>
<tr>
<td>Longitude</td>
<td>Decimal degrees</td>
<td>Observation network</td>
</tr>
<tr>
<td>First observation year</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>Last observation year</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>Temporal sampling frequency</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>Land use/land cover</td>
<td></td>
<td>Observation network/NLCD 2006</td>
</tr>
<tr>
<td>Number of sampling depths</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>Depth of each sample</td>
<td>cm</td>
<td>Observation network</td>
</tr>
<tr>
<td>Percent sand/silt/clay</td>
<td>%</td>
<td>Observation network/SSURGO</td>
</tr>
<tr>
<td>Soil texture class</td>
<td></td>
<td>Observation network/SSURGO</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity</td>
<td>$\mu$m s$^{-1}$</td>
<td>Observation network/SSURGO</td>
</tr>
<tr>
<td>Bulk density</td>
<td>g/cm$^3$</td>
<td>Observation network/SSURGO</td>
</tr>
<tr>
<td>Sampling probe type</td>
<td></td>
<td>Observation network</td>
</tr>
<tr>
<td>Elevation</td>
<td>ft</td>
<td>Observation network</td>
</tr>
<tr>
<td>Representative SSURGO polygon</td>
<td></td>
<td>SSURGO</td>
</tr>
</tbody>
</table>

* These parameters are available for all depths at which soil moisture is measured.
when a number of the networks that contribute data to the NASMD already perform some type of QC. It is also reasonable to ask whether the errors in the soil moisture data will have a significant impact on the value of soil moisture data for practical applications and scientific studies. These questions were addressed by Xia et al. (2015c). They developed an automated soil moisture QC method for a subset of stations from the NASMD using the North American Land Data Assimilation System phase 2 (NLDAS-2) Noah soil porosity, soil temperature, and fraction of liquid and total soil moisture. Overall, the results of Xia et al. (2015c) demonstrate that it is necessary to perform QC on all of the soil moisture data, even for networks that already have their own QC routines. They also found that removing the soil moisture measurements that were flagged by their QC procedure had a significant positive impact on the agreement between NLDAS-2 model-simulated and observed soil moisture, especially in Alabama, North Carolina, and west Texas. Therefore, based on the results of Xia et al. (2015c), we conclude it is necessary to develop an appropriate quality control procedure for the NASMD and that this procedure should be applied to all stations.

Soil moisture is influenced by several physical, site-specific characteristics including soil properties (e.g., texture, organic matter, structure), land cover, and climate conditions (e.g., precipitation, temperature, solar radiation). Thus, the ideal QC method uses site-specific characteristics to assess the data validity. You et al. (2010) describe examples of such techniques employed by the AWDN when quality controlling soil moisture data such as the precipitation-and-irrigation-based method, which evaluates whether changes in soil moisture are accompanied by precipitation or irrigation. Similarly, the precipitation and irrigation amount test assesses whether a single time step rise in soil moisture exceeds the total precipitation plus irrigation amount (You et al. 2010). Such robust tests provide physically based methods of data validation instead of the purely statistical methods employed by many (Durre et al. 2010; Dorigo et al. 2011). However, these techniques can only be applied when ancillary data such as temperature, precipitation, irrigation (if applicable), and soil porosity are available. Unfortunately, the majority of stations in the NASMD do not have enough ancillary data to use physically based techniques and so only statistical-based approaches are used to QC the NASMD.

We have chosen to utilize the same QC algorithm for all stations in the NASMD because our goal is to provide a harmonized soil moisture dataset (i.e., harmonized with respect to measurement units, time step, metadata, and QC procedures). We believe that there is significant value in building a harmonized dataset and that it has the greatest utility (and is most appropriate) for those who are interested in using data from the NASMD since many applications require data from multiple soil moisture networks. We also make the original data available so that those who are interested in developing their own QC procedures, or using data that have not undergone QC, may do so.

Soil moisture data are processed before entering the NASMD QC algorithm to convert data from different observation networks into the same format. Because different observation networks measure soil moisture at different soil depths, data from each network are processed separately in the QC procedure. The algorithm was developed as a set of MATLAB scripts, which, together, take...
approximately 10–20 min to process a network’s worth of data, depending on the size and time length of the network observations. The NASMD QC procedure was developed similarly to the algorithms used successfully by the Oklahoma Mesonet, West Texas Mesonet, and AWDN. The algorithm includes tests for soil moisture range, persistence, magnitude, and variability.

**Range/integrity test.** Volumetric soil water content represents the volume of water contained in a specified soil column divided by the total soil column volume and, thus, cannot be less than 0 or exceed 1. In reality, volumetric water content cannot physically exceed soil porosity, with the rare exception of supersaturated soils. The range test thus removes any values that do not fall within the range of 0 to 0.6. This test is similar to the range test that is described in Hubbard et al. (2005) and is used by the AWDN for soil moisture data validation. The integrity test is similar to that described by Durre et al. (2010) employed by the Global Historical Climatology Network (GHCN). This procedure checks for sampling day replication and validates the date labels as well as each site’s reported latitude and longitude. The integrity test’s purpose is to ensure that in subsequent QAQC steps, data will only be flagged or removed as a function of the data itself and not labeling or conversion issues.

**Streak (persistence) test.** The streak test assesses soil moisture variability over time. Soil moisture observations are removed if the same value is recorded every day over a >10-day period. Considering soil moisture’s highly variable nature, sensor records of the same value over such a long period is assumed to be sensor failure and not valid data. The 10-day threshold was selected examining a range of thresholds ranging from 5 to 50 days using data from several networks and geographic regions. We acknowledge that the variability of daily volumetric water content is a strong function of climate and soil texture (and as sensor type). However, even when conditions are very wet or very dry, there are small variations in the soil moisture measurements (especially given that it is measured to the thousandth decimal). For example, even deep in the soil profile (100 cm) in an arid location like Walnut Gulch, Arizona, there are small day-to-day variations in soil moisture and rarely are the exact water content values reported on two consecutive days (results not shown).

Similar to the persistence test described by Shafer et al. (2000) used by the Oklahoma Mesonet, our streak test cannot discern when the sensor failed and thus the entire streak of similar values is flagged.

**Deviance (magnitude) test.** The deviance test assesses if the absolute magnitude of a soil moisture measurement is valid based on previous measurements during that period of time. The method calculates the mean and standard deviation of a 30-day window surrounding each day of the year over all years of measurement. The daily measurement in question is then converted to a z score by subtracting the window mean and dividing by the window standard deviation. Daily observations are flagged if their respective z score is greater than 3. Essentially the procedure flags observations that deviate more than three times the standard deviation, calculated from average soil moisture conditions typical of that period of time. The deviance test is similar to the outlier check described by Durre et al. (2010) and used by the GHCN. Given that 3 standard deviations covers 99.73% of the distribution, it is possible that using this threshold will occasionally result in rejecting a true extreme value. However, based on our testing, this threshold appears to perform well and does not result in too many true measurements being rejected.

![Fig. 3. Soil moisture plots from 5- and 25-cm depths in Acme, Oklahoma, in 2000. There are two plots of the soil moisture data from each depth. (a),(c) The soil moisture data before it has been filled by the DAR procedure and (b),(d) the soil moisture data after infilling.](image-url)
Soil moisture at shallower depths exhibits considerable intraannual variability; however, interannual variability is typically much less. Table 3 displays average daily coefficient of variation (CV) at nine observation networks between measurement years, calculated using the same 30-day window employed in the deviance test. Minimum, maximum, and mean CV values are reported, representing the depth at which the lowest and highest variability was observed, as well as the average variability between all depths. The West Texas Mesonet data exhibit the highest variability from year to year; however, the maximum variability was still only 0.34, meaning that the data standard deviation is one-third of the 30-day window mean.

<table>
<thead>
<tr>
<th>Network</th>
<th>Minimum CV</th>
<th>Maximum CV</th>
<th>Mean CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM</td>
<td>0.03 (175 cm)</td>
<td>0.09 (5 cm)</td>
<td>0.06 (8)</td>
</tr>
<tr>
<td>AWDN</td>
<td>0.01 (100 cm)</td>
<td>0.12 (10 cm)</td>
<td>0.07 (4)</td>
</tr>
<tr>
<td>Cosmos*</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05 (1)</td>
</tr>
<tr>
<td>CRN</td>
<td>0.10 (100 cm)</td>
<td>0.16 (5 cm)</td>
<td>0.13 (5)</td>
</tr>
<tr>
<td>DEOS</td>
<td>0.14 (5 cm)</td>
<td>0.14 (5 cm)</td>
<td>0.14 (1)</td>
</tr>
<tr>
<td>ECONet</td>
<td>0.26 (20 cm)</td>
<td>0.26 (20 cm)</td>
<td>0.26 (1)</td>
</tr>
<tr>
<td>Illinois Climate Network</td>
<td>0.08 (150 cm)</td>
<td>0.23 (5 cm)</td>
<td>0.16 (6)</td>
</tr>
<tr>
<td>Oklahoma Mesonet</td>
<td>0.07 (75 cm)</td>
<td>0.10 (5 cm)</td>
<td>0.09 (4)</td>
</tr>
<tr>
<td>West Texas Mesonet</td>
<td>0.28 (75 cm)</td>
<td>0.34 (5 cm)</td>
<td>0.31 (4)</td>
</tr>
</tbody>
</table>

* COSMOS reports a single volume-integrated soil moisture value; the depth varies in space and time.

Step test. The step test assesses the change in magnitude between consecutive measurements. The procedure calculates the average and standard deviation of the difference between consecutive measurements for each site. Similar to the deviance test, each daily “step” value is converted into a z score using the magnitude difference average and standard deviation. Observations are flagged if their respective z score is greater than 3.

Observations that are flagged by the streak (persistence) test are immediately removed; however, the deviance and step tests are complimentary such that an observation is only removed if it is flagged by both tests. The deviance and step tests work off of each other because of the nature of extremely dry or wet events. The deviance test flags extreme events that diverge from the time period mean by more than three times the standard deviation. Thus, if an extreme precipitation event occurs, the likelihood of the deviance test flagging the corresponding soil moisture observation is increased. However, the aforementioned soil moisture observation is not removed if the step test shows that the next daily value is also considerably higher than normal. This is the case as the “normal” soil moisture response to heavy precipitation is a dramatic increase with a gradual decrease (Illston et al. 2008). Any anomalously high soil moisture observation is removed only if the previous and subsequent observations are at or below normal, suggesting a sensor failure instead of a large precipitation event.

Figure 4 shows 25-cm soil moisture data from October 2003 to September 2004 at Ashton, Kansas. The data that were not flagged by the deviance test are immediately removed; however, the deviance and step tests are complimentary such that an observation is only removed if it is flagged by both tests. The deviance and step tests work off of each other because of the nature of extremely dry or wet events. The deviance test flags extreme events that diverge from the time period mean by more than three times the standard deviation. Thus, if an extreme precipitation event occurs, the likelihood of the deviance test flagging the corresponding soil moisture observation is increased. However, the aforementioned soil moisture observation is not removed if the step test shows that the next daily value is also considerably higher than normal. This is the case as the “normal” soil moisture response to heavy precipitation is a dramatic increase with a gradual decrease (Illston et al. 2008). Any anomalously high soil moisture observation is removed only if the previous and subsequent observations are at or below normal, suggesting a sensor failure instead of a large precipitation event.

Figure 4 shows 25-cm soil moisture data from October 2003 to September 2004 at Ashton, Kansas. Data shown in blue were not flagged by the deviance and step tests while data in red were flagged.
and step tests are shown in blue, while the data that were flagged are shown in red. The flagged data show a rapid soil moisture increase, well above the deviance test threshold, possibly the cause of a strong precipitation event. However, after a couple of days, soil moisture decreases nearly as rapidly. This is not the normal response of a drying soil and is more indicative of sensor failure. Thus, these data were also flagged by the step test and subsequently removed. A month later, soil moisture similarly increases rapidly, but subsequently decreases gradually in a way that is much more indicative of a drying soil. Since these data were not flagged by both the deviance and step tests, they were not removed.

The four validation tests that constitute the NASMD QAQC algorithm—the range, streak, deviance, and step tests—flagged 0.67%, 0.52%, 4.40%, and 3.22%, respectively, of the >8 million values soil moisture data that have been assessed by the QC procedure. By way of comparison, the soil moisture quality control methodology developed by Dorigo et al. (2013) flagged approximately 13% of the soil moisture measurements in the ISMN.

**APPLICATIONS.** Soil moisture exhibits substantial variability on daily, monthly, seasonal, and interannual time scales (Illston et al. 2004). Soil moisture persistence ranges from several days to several months depending on the soil layer depth and overlying climatic conditions (Georgakakos and Bae 1994; Wu et al. 2002; Wu and Dickinson 2004). Seasonal soil moisture anomalies have been shown in models to influence weather patterns and precipitation in subsequent seasons (Oglesby and Erickson 1989; Meng and Quiring 2010; Hirschi et al. 2011). We use in situ soil moisture observations from several networks contained within the NASMD to explore the variability of soil moisture on intraannual and interannual time scales.

**Intraannual variability.** Soil moisture data from five networks, totaling 196 stations across the United States, are used to examine intraannual variability. Figure 5 shows a map of these networks, specifically the Atmospheric Radiation Measurement (ARM), the Delaware Environment Observing System (DEOS), the North Carolina Environment and Climate Observing Network (ECONET), the Illinois Climate Network (ICN), and the Michigan Automated Weather Network (MAWN). These networks were chosen for their data completeness and record length. Soil moisture measurement depths vary depending on the network (Table 1). To assess intraannual soil moisture variability, daily volumetric soil water content data from all sites within each network were plotted together spanning 1 January to 31 December. Soil moisture is occasionally measured in frozen soils for the MAWN and ICN networks, which typically results in unrealistically low soil moisture measurements. We identify frozen soils using daily soil temperature measurements from these networks. As described above, the NASMD QC algorithm does not utilize soil temperature data to flag observations because soil temperatures are not available for all networks. For the purposes of this analysis, daily soil moisture observations taken in frozen soils are removed before analyzing intraannual variability. Figures 6a–d show intraannual variability of near-surface (5 to 10 cm) soil moisture from ARM, DEOS, ICN, and MAWN networks, respectively. The ECONET network only measures soil moisture
at 20 cm and therefore it is not included. Figures 6a, 6b, and 6c show that there is a strong seasonal cycle in the near-surface soil moisture at ARM, ICN, and DEOS stations. Soil moisture observations from the first three networks show maximum soil moisture values during the late winter and early spring and this is followed by a consistent period of drying during the summer. These patterns are similar to those found in Illinois by Hollinger and Isard (1994) and in Oklahoma by Illston et al. (2004).

Figure 6d shows the intraannual variability of soil moisture measured at 10 cm for the MAWN stations that are located in Michigan and Door County, Wisconsin. Data from MAWN exhibits higher interstation variability and less seasonal variation than the other four networks. One possible explanation is that land cover over MAWN network sites is more diverse than other networks. For example, the majority of ARM and ICN sites are surrounded by grassland landscapes while MAWN sites’ land cover ranges from mixed forest to bog. These patterns may also arise because of differences in the time period, soil characteristics, climate conditions, instrumentation, and depth of measurements between the networks.

Figures 7a–d show similar plots as Fig. 6 only for deeper measurements of soil moisture. Data are plotted from the ARM network at 35 cm, the ECONET network at 20 cm, the ICN network at 50 cm, and the MAWN network at 25 cm. Seasonal variability of deeper soil moisture is similar to that of the near surface (Fig. 6); however, the signal is somewhat dampened. This agrees with the findings of Wu et al. (2002), who found that the amplitude of Illinois soil moisture response to precipitation variability decreased with soil depth. In general, soil moisture at three of the four networks shows considerable seasonal variability. Our results illustrate that soil moisture can vary significantly within networks and between networks owing to the large number of factors that influence soil moisture.

Interannual variability. Data contained in the NASMD can also be used to examine the interannual variability...
of soil moisture across North America. Soil moisture variability, both seasonal and interannual, is tied to precipitation variability. Therefore, soil moisture interannual variability over a number of years can represent drought variability in that particular region. Stations from the ARM and ICN networks were used to analyze soil moisture interannual variability following the approach of Fan et al. (2011). Figure 8 shows mean monthly soil moisture anomalies (departures from the long-term mean) averaged over all sites within each network. Soil moisture anomalies represent relative soil wetness with respect to normal conditions for that location and time of year and they are useful for drought monitoring, especially in regions with heterogeneous climate and soil conditions. Monthly soil moisture anomalies, as shown in Fig. 8, can be used to examine the development and progression of soil moisture–drought. Figure 8 shows how drought conditions develop and tend to move down through the soil profile. It also depicts how soils recover from drought conditions and illustrates that soil moisture can vary significantly with depth. For example, Fig. 8a shows a sudden onset of below normal soil moisture in the latter half of 1999. These drier-than-normal conditions appear relatively consistent throughout the soil profile during the first month of the drought. Interestingly, the drought event in 1999/2000 appears most pronounced between 50 and 100 cm in the soil and the soil moisture anomalies near that surface and at depth are somewhat smaller. Conditions improve in the first half of 2000 and some wet anomalies are seen near the surface; however, this improvement is not felt at depth and the soil moisture conditions below 100 cm do not recover until 2002. The recovery in 2002 shows that although the near-surface soil moisture recovers right away, it takes a number of months of above normal rainfall (not shown) before the deeper layers of the soil recover. This can be seen by the slope of the red contours (e.g., the −4 contour) in early 2002. In contrast, the onset of the 2006 drought event was quite different (Fig. 8b). During the early part of the 2006 event there are large negative soil moisture anomalies in the upper 70 cm of the soil, but below that the soil is wetter than normal. As the dry conditions

Fig. 7. Middle layer soil moisture from (a) ARM 35 cm, (b) ECONET 20 cm, (c) ICN 50 cm, and (d) MAWN 25 cm. Each line represents one station during 1 year of measurement.
persist, the entire soil profile continues to dry out, particularly during the summer of 2006. Once these dry conditions reach 150 cm, they persist for almost a year. Again, the recovery of the deeper layers lags the near surface by several months.

Figures 8c and 8d show the monthly average soil moisture anomalies from 2004 to 2012 from the ICN stations. ICN record shows a prolonged period of anomalously dry soils between March 2005 and March 2008 interspersed with brief periods of normal soil wetness. Similar to ARM, visualizing soil moisture conditions in this way illustrates that moisture conditions in the soil profile are rarely homogeneous and that the response of the deeper soil layers significantly lags the surface.

Utility of soil moisture for drought monitoring. Hundreds of drought indices and monitoring and forecasting systems exist, each producing slightly different interpretations of drought and its impacts. Soil moisture is an excellent proxy for agricultural drought as anomalously dry/wet soils influence the amount and rate of crop root uptake and surface runoff. Several previous studies have used soil moisture for agricultural drought monitoring (Quiring and Papakryiakou 2003; Narasimhan and Srinivasan 2005; Bolten et al. 2010). We use soil moisture data provided to the NASMD by the Oklahoma Mesonet to examine how well drought can be characterized with soil moisture. The Oklahoma Mesonet operates over 120 stations across the state of Oklahoma, measuring several meteorological variables at subhourly resolution (Illston et al. 2004).

We directly compare Oklahoma drought conditions to those reported over the same period by the U.S. Drought Monitor (http://droughtmonitor.unl.edu/). The U.S. Drought Monitor is a drought monitoring framework produced jointly by the National Oceanic and Atmospheric Administration, the U.S. Department of Agriculture, and National Drought Mitigation Center, and the University of Nebraska–Lincoln. The Drought Monitor product is a blend of several drought indicators including precipitation and temperature anomalies, satellite-derived vegetation productivity, and modeled soil moisture. The Drought Monitor represents drought intensity as one of five classes, from least to most intense: abnormally dry (D0), moderate drought

Fig. 8. Observed vertical profile of column soil moisture anomalies (mm of soil water/10) for ARM and ICN networks: (a) ARM soil moisture anomalies for 1998 to 2004, (b) ARM soil moisture anomalies for 2004 to 2010, (c) ICN soil moisture anomalies for 1998 to 2008, and (d) ICN soil moisture anomalies for 2008 to 2011. ARM soil moisture anomalies are calculated using 1998 to 2010 to calculate mean soil water content at each depth: 5, 15, 25, 35, 60, 85, 125, and 175 cm. ICN soil moisture anomalies are calculated using 2004 to 2011 to calculate mean soil water content at each depth: 5, 10, 50, 100, and 150 cm. Positive anomalies (wetter-than-normal conditions) are shown in blue and negative anomalies (drier-than-normal conditions) are shown in red.
(D1), severe drought (D2), extreme drought (D3), and exceptional drought (D4). Drought is reported weekly as a percent of a geographic region (e.g., state) in each drought category. To compare soil moisture from the Oklahoma Mesonet to Drought Monitor reports of Oklahoma drought, we used the measurements of daily volumetric water content at 5 cm and then converted these measurements to percentiles based on 2000 to 2013 data for 100 stations in Oklahoma. Percentiles were averaged for each 7-day period between 2000 and 2013 to match the resolution of the Drought Monitor, and drought classes were determined based on the weekly percentiles. Finally, the percent of the state of Oklahoma in each drought category for every week was calculated as the number of Oklahoma Mesonet stations in each category divided by the total number of stations (n = 100). This allowed us to directly compare drought onset, intensity, and duration represented by soil moisture anomalies with that reported by the U.S. Drought Monitor. Although the Oklahoma Mesonet measures soil moisture at 5, 25, 60, and 75 cm, the soil moisture percentiles that are used to generate Figs. 9 and 10 are based on the 5-cm measurements. In previous studies we have evaluated using measurements from other depths (or the entire soil column) and found that using measurements from deeper in the soil column does not improve the results (e.g., Ford and Quiring 2013, 2014a). Although these findings seem somewhat counterintuitive, they have been evaluated multiple times and we believe they are robust. Of course, only using the 5-cm measurements means that there is significantly more variability (noise) in the data.

Figure 9 shows the evolution of drought, as represented by the percent of Oklahoma in each drought category, events between 2000 and 2013. The top plot shows the U.S. Drought Monitor and the bottom plot shows drought from Oklahoma Mesonet soil moisture anomalies. Oklahoma has experienced a number of severe drought events over the last 12 years, including particularly extensive events from 2002 to 2003, 2005 to 2007, and 2010 to 2012. These events are well represented in both datasets; however, the U.S. Drought Monitor shows much more spatially extensive and longer duration drought events than the soil moisture. This could be attributed to the large influence precipitation events have on near-surface soil moisture. This is one drawback to using 5-cm soil moisture measurements. During the very extreme drought events (2006, 2011), a single precipitation event does not provide enough relief to alleviate the drought indices that are used to develop the U.S. Drought Monitor. However, one precipitation event is enough to increase near-surface soil moisture enough that it reduces the severity of drought conditions (i.e., soil moisture percentile) for a short period of time.

Three major drought events in Oklahoma between 2000 and 2013 are examined in greater detail using both records (Fig. 10). The drought events occur between (Fig. 10a) 2000 and 2002, (Fig. 10b) 2005 and 2007, and (Fig. 10c) 2010 and 2012. Events from 2000 to 2002 and 2005 to 2007 are captured by both records. Drought onset is months earlier in the soil moisture record than the U.S. Drought Monitor. However, drought demise roughly occurs at the same time in both datasets. The spatial extent of the 2000–02 drought across Oklahoma as represented by the Drought Monitor is consistently larger than the soil moisture record, although the peak drought severity (drought class) is higher in the soil moisture record (Fig. 10a). Similarly, the 2005–07 drought onset is earlier in the soil moisture dataset, but it is not as spatially extensive as represented by the Drought Monitor (Fig. 10b).

The large drought event occurring between mid-2010 and early 2012 is considered one of the most severe drought events to influence the southern Great Plains in the last century (Hoerling et al. 2013). The onset and demise of the event (Fig. 10c) are
similar for both datasets; however, the spatial extent and overall severity is much larger in the Drought Monitor representation than the soil moisture dataset. Throughout 2011, the percent of Oklahoma in each drought event peaks and troughs in the soil moisture dataset, attributable to short time periods of rainfall. Soil moisture can be used to represent drought conditions; however, the duration and spatial extent of soil moisture drought may not be reflective of general agricultural or hydrologic conditions, particularly during severe, long-lasting drought. That being said, the near-surface soil moisture measurements from the Oklahoma Mesonet responded to drier-than-normal conditions immediately preceding drought events much more quickly than the U.S. Drought Monitor. This suggests that a spatially extensive network of in situ soil moisture observations can be used to provide timely drought early warning in the United States.

**DISCUSSION.** Web-based application. The NASMD website is available at [http://soilmoisture.tamu.edu/](http://soilmoisture.tamu.edu/). Our online system allows the user to query the entire database to find data that meet their research needs. Users may query the database not only to find soil moisture in a specific geographic region or time period, but queries based on metadata are also possible. For example, a user may select only soil moisture observations that were taken at the 5-cm depth in soils with less than 20% sand content or select all soil moisture observations from networks using heat dissipation sensors. The website will also allow the user to download all of the metadata along with the soil moisture observations, including sensor change/recalibration dates. Data and metadata from all sites can be downloaded directly from the NASMD online platform. All orders are queued and data are delivered via a zipped folder to the user’s desired e-mail address.

![Fig. 10. Area plots showing the percent of Oklahoma in drought between (a) 2000 and 2002, (b) 2005 and 2007, and (c) 2010 and 2012. Areas are color coded by drought severity. The top plots in each panel show the U.S. Drought Monitor and the bottom plots are from soil moisture measured at Oklahoma Mesonet stations.](image)
the NASMD is the utility of soil moisture observations for validating land surface models and satellite-derived soil moisture estimates. Numerous studies employ land surface models (LSM) to investigate land–atmosphere interactions as well as interannual and interdecadal climate variability. However, significant model-to-model variations in LSM-estimated soil moisture combined with a lack of observational soil moisture data make it difficult to adequately assess the accuracy of LSM-estimated soil moisture (Robock et al. 2003; Schaake et al. 2004). Oleson et al. (2004) found that the NCAR Community Land Model (CLM) version 3.5 has a wet soil moisture bias and systematically underestimates soil moisture variability. Other studies have found that previous versions of CLM and similar LSMs also have issues and biases related to vegetation and soil parameterizations (Oleson et al. 2008; Jiang et al. 2009). The NASMD and other soil moisture data sources provide accurate, in situ observations by which these models can be calibrated and validated. For example, Ford et al. (2014b) used data from the NASMD to compare the model-derived and observed soil moisture–energy flux relationships. They found that the relationships between soil moisture and evaporation/latent heat are highly variable in time and space. This is only one example of how observed soil moisture can be used to evaluate and improve our understanding of model-simulated land–atmosphere interactions. Of course it should be noted that many land–atmosphere studies, including Ford et al. (2014b), also utilize other measurements of energy and water fluxes and so locations with flux tower are particularly valuable. There are a total of 96 stations in the NASMD that are collocated with flux towers [AmeriFlux (58 stations), ARM (17 stations), and Fluxnet Canada (21 stations)].

Observed soil moisture also has utility for forecasting the occurrence of extreme heat. Ford and Quiring (2014) examined the statistical relationship between monthly extreme temperatures and observed soil moisture in Oklahoma using quantile regression. They found that soil moisture most strongly impacts extreme heat events at the high end of the conditional distribution, suggesting that soil moisture anomalies have the largest impact on the most extreme heat events. They also assessed the potential of soil moisture for predicting the probability of extreme heat events using soil moisture from the previous month and demonstrated that the skill of these forecasts is comparable to the NOAA Climate Prediction Center monthly mean temperature forecasts (2-week lead time).

Several recent studies have employed satellite-estimated soil moisture to investigate land–atmosphere interactions and possible soil moisture trends. Taylor et al. (2011) employ land surface temperature data as a proxy for soil moisture variability to examine spatial patterns and frequency of convective storm initiation in the Sahel. They found that over a third of all storm initiations occurred over areas with the steepest land surface temperature (soil moisture) gradients. Dorigo et al. (2012) used soil moisture estimated in a merged microwave-based dataset to examine global soil moisture trends over the last two decades. They were able to identify various regions of the globe with strong wetting and drying trends. Ford et al. (2014a) showed that mean absolute differences between standardized soil moisture data from the Oklahoma Mesonet and remote sensing retrievals from the Soil Moisture and Ocean Salinity (SMOS) platform varied from 0.14 to 0.43 (cm$^3$ cm$^{-3}$). Satellite soil moisture products can provide an accurate depiction of large-scale soil moisture variability; however, extensive validation is necessary to estimate the accuracy of the satellite-derived soil moisture products. Observed soil moisture from the NASMD will aid in the validation of satellite-based soil moisture estimates employed by these and similar studies as well as the calibration of satellite platforms estimating soil moisture such as the Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) missions.

**SUMMARY.** The North American Soil Moisture Database provides in situ soil moisture observations from nearly 2,000 sites across the United States, Canada, and Mexico. Data contributed from observation networks are integrated into the NASMD, quality controlled using the QAQC algorithm, and are provided to users via a centralized web-based portal. Several data products are available including the “raw” volumetric soil water content product from the observation networks, data that are quality assured by the NASMD, data that are gap filled using the DAR infilling process, and standardized gridded soil wetness data.

The NASMD is a retrospective database for soil moisture data and thus it has primarily been designed to support research applications. Typically, soil moisture data are updated every 6 months. Obviously this is not suitable for applications such as drought monitoring. Therefore, a parallel effort is underway to provide real-time soil moisture data. The President’s Climate Action Plan calls for the development of a National Drought Resilience Partnership that will manage drought-related risks by linking information with drought preparedness and longer-term resilience strategies. One component of the National Drought Resilience Partnership is developing a
coordinated national soil moisture network. A workshop was organized by the National Integrated Drought Information System (NIDIS) to articulate a plan of action for development of a coordinated National Soil Moisture Network. The aim of the workshop, which was held in Kansas City, Missouri (November 2013), was to take stock of federal and state in situ monitoring networks, satellite remote sensing missions, numerical modeling capabilities, and how to merge these capacities into a network of networks providing a comprehensive suite of national real-time soil moisture products. As a result of this workshop, NIDIS funded the development of pilot soil moisture monitoring system. This project, which is jointly being led by the USGS Center for Integrated Data Analytics and Texas A&M University, will develop a common, robust infrastructure to integrate and serve disparate soil moisture data from distributed systems and support a suite of value-added soil moisture tools and visualizations. Other recent events, such as the launch of NASA SMAP mission on 31 January 2015 and the upcoming release of NLDAS-3 (which will provide modeled soil moisture for the North American domain on a 1/32° grid) highlight that we are entering a new era that will provide unprecedented access to new soil moisture datasets that can be used to improve drought monitoring and forecasting, calibration/validation satellites and land surface models, and documenting how soil moisture influences the climate system on seasonal to interannual time scales.

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REFERENCES


—, P. Gentine, B. R. Lintner, and C. Kerr, 2011: Probability of afternoon precipitation in eastern United States and Mexico enhanced by high


Tang, C., and T. C. Piechota, 2009: Spatial and temporal soil moisture and drought variability in the Upper


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RESEARCH APPLICATIONS HISTORY
WORLDWIDE SURVEY OF AWARENESS AND NEEDS CONCERNING REANALYSES AND RESPONDENTS VIEWS ON CLIMATE SERVICES


Results of a worldwide online survey for reanalysis users provide valuable insight for removing obstacles that hinder the use of reanalyses in climate services.

The World Meteorological Organization (WMO) defines climate services as the provision of climate information prepared and defined to meet users’ needs (WMO 2011). Such climate services could thus include a variety of sector-specific climate research (e.g., Hartmann et al. 2013), including investigations into past, current, and future climate as well as associated observed and projected trends. The process of linking the climate data production with user demands is a complex one (McNie 2013) and requires codesign (Bradwell and Marr 2008). WMO also emphasizes that the development of climate services should extend beyond traditional meteorological information to encompass nonmeteorological data in the areas of agriculture, health, infrastructure, and various other socioeconomic considerations.

There are increasing efforts to improve the delivery of climate services at national, regional, and global levels. These efforts include Global Framework for Climate Services (GFCS; Hewitt et al. 2012) and Copernicus Climate Change Service (C3S). The aim of the GFCS, led by WMO, is to strengthen the provision and use of climate predictions, products, and information worldwide, and the vision of the C3S is to provide an authoritative source of quality-assured climate information for Europe and globally. Furthermore, a European research and innovation Roadmap for Climate Services has been recently
elaborated by an expert group established by the European Commission (Street et al. 2015).

Given the scales and ambition of envisaged climate services, there are many challenges to be addressed. Among other contributory factors, two salient considerations may be highlighted: 1) The climate services’ end user community is not fully known in advance; besides well-known, identifiable users (e.g., governments at various levels), the need for climate-sensitive information pervades many areas of society, and so the user base is poised to grow with the increased accessibility of information. 2) Even if the needs of an end user group were very well known, it may not be straightforward to fully meet them. For example, when delivering observational data, the inevitable limitations of the observing systems need to be acknowledged. Neither in situ measurements nor remotely sensed ones cover all the temporal and spatial scales that are requested by users. Both considerations should be kept in mind when addressing the challenging question of whether a produced and delivered piece of climate information is fit for purpose.

Typically, climate observations are generated by a diverse combination of instrumentation and computational processing, and the observation density changes over time and location. For these reasons, careful harmonization of observational datasets is essential. A range of different techniques are available for interpolating spatially irregular marine and meteorological observations to regular grids. Examples include the European daily high-resolution gridded dataset (E-OBS) for Europe (Hofstra et al. 2008), the Global Historical Climatology Network for land station observations (Menne et al. 2012), the International Comprehensive Ocean–Atmosphere Dataset for surface marine observations (Woodruff et al. 2011), and the Global Precipitation Climatology Centre (Becker et al. 2013) at the global scale, in addition to many products at national levels, for example, over Finland (Aalto et al. 2013).

Besides utilizing gridded climate observational datasets, climate service provision may benefit from assimilation-based reanalysis activities. These extend beyond traditional reanalysis dataset production to related activities such as observational dataset evaluation. Currently there are more than 15 (40) atmospheric (oceanic) global reanalyses produced by different institutions. The reanalysis systems employed aim for a consistent analysis of archived Earth observations (preferably those that have undergone reprocessing; Bosilovich et al. 2013), using a modern analysis and forecasting system (Dee et al. 2014). With such systems it is possible to derive estimates for the atmosphere–ocean–Earth system state in a scientifically traceable manner and approaching the quality needed for the most demanding climate applications. The assimilation-based algorithms spread information from observed parameters and locations to times and locations where the in situ or satellite data coverage is poor or nonexistent.

For supporting climate services, there is a growing need for characterization and communication of dataset uncertainties. This applies both to “purely observational” datasets (e.g., in case of the E-OBS dataset; Hofstra et al. 2010) and to reanalysis datasets. The comprehensive range of geophysical parameters and spatiotemporal scales available in a reanalysis dataset, together with the complexities of modern analysis/forecast techniques, means that reanalysis uncertainty characterization is a significant challenge. It requires a close and sustained cooperation between reanalysis producers and the wider climate service community, including the user application and science communities. Mechanisms to facilitate the sharing of knowledge will be vital, and we thus acknowledge the richness of the exchanges and comments posted on the community forum website reanalyses.org.

With such considerations in mind, it was decided to conduct a worldwide user survey of awareness and needs concerning reanalyses and climate services. The main aim was to gather responses that would inform future development of reanalyses in support of climate services. A goal of the survey was also to foster discussion with users with a view to engaging in closer cooperation. A previous reanalysis user survey, namely, about 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005), was conducted in 2004/05 (Holingsworth and Pfang 2005). Most of the 127 respondents gave positive feedback about the quality and accessibility of the ERA-40 data. That survey revealed that users desired increased resolution, longer time spans, and more regular extensions of the time series to the present. Despite the relatively small number of respondents, the survey provided valuable input for shaping the definition of ECMWF interim reanalysis (ERA-Interim; Dee et al. 2011) and ECMWF twentieth-century pilot reanalysis (ERA-20C; Poli et al. 2013), with the former continuing into the present and the latter covering the entire twentieth century.

The new survey reported in the current article was conducted in the period from November 2013 to February 2014. The survey elicited responses from
2,578 users of climate information drawn from 10 sectors (private, education, etc.) and 28 fields of work (weather, climate, ecosystems, etc.). Recognizing the interest within the GFCS and C3S in agriculture and food security (Tall et al. 2014), disaster risk reduction, health and water resources, and, since 16 January 2015, also energy [WMO summary statement on the Second Session of the Intergovernmental Board on Climate Services (IBCS-2) conference], we present analyses of all responses as well as responses from sectoral groups who focus their work on water management, agriculture, forestry, and energy. The results summarized in this paper are offered as a contribution to wider consultation processes for shaping global, intergovernmental, and national climate service initiatives.

MATERIAL AND METHODS. Survey scope, advertising, and response rate. Our survey aimed at ascertaining user awareness and needs concerning reanalyses to guide the development of reanalyses in support of climate services. Devised and conducted within the frame of a European-funded coordination project [Coordinating Earth Observation Data Validation for Re-Analysis for Climate Services (CORE-CLIMAX)], we nonetheless sought and accepted responses worldwide. The respondents were queried about four main themes: 1) demographics and scientific background, 2) their use of data and applications, 3) their awareness and needs in regard to reanalyses, and 4) their perceptions of climate services. For each theme, two or three main questions were presented with several subsections (more information can be found online at http://dx.doi.org/10.1175/BAMS-D-14-00271.2). This paper briefly addresses themes 1 and 2 with an emphasis on themes 3 and 4.

The survey was put online for around 105 days. It was launched on November 2013 by the Finnish Meteorological Institute (FMI) and by WMO; the latter sent an invitation letter (see the supplemental information, section labeled “Please take part in the reanalysis user and application survey”) to its focal points who then distributed it further. During the next two weeks, the survey was posted on the project web pages, on FMI internal web pages, and, with help from the National Oceanic and Atmospheric Administration (NOAA), on reanalyses.org. The closing of the survey was originally scheduled for the end of January 2014, but it was later postponed by a month (see the supplemental information).

The number of respondents first grew only gradually (Fig. 1). During the first two months the total number of respondents was 183 (and 64 left their contact information, hereafter CON). On 21–22 January a very successful effort was made to increase the response rate, as NOAA advertised the survey to the reanalysis community by sending messages to reanalysis_20cr-notify, all of NOAA Earth System Research Laboratory (ESRL), all of University of Colorado (CU)/Cooperative Institute for Research in Environmental Sciences (CIRES), and acre-discussion@met-acre.org, and ECMWF sent an e-mail to its registered users. Within the next five days we received an additional 1,332 responses (463 CON). During 26 January–23 February, the number of respondents increased by 203 (85 CON). A reminder by ECMWF on 24 February resulted in a new sharp peak, with 860 responses (292 CON) during the last five days before the survey was closed. That means that during the two 5-day periods, one in January and the other in February, following the e-mails from NOAA and ECMWF, altogether 2,192 respondents (755 CON) took part in the survey. Thus, we suspect that most of these respondents were directly influenced by the advertisements, whereas many of the remaining respondents (386 in total, 149 CON, or about 15%) may have found the survey link more independently.

Collecting background information about the survey respondents. The first two of the four main themes that the respondents were queried about concerned demographics and scientific background (Q1–Q3, Q12) and the use of data and applications (Q4–Q6; see the supplemental information, section labeled “Reanalysis user and application survey”). Because the survey primarily focused on finding the specific needs of the respondents for the scientific development of reanalyses and climate service portfolio, traditional demographical information such as age, gender,
For question Q8 (“Regarding the characteristics of reanalysis data, would you say that...?”), a total of 23 statements were proposed, asking users to express their level of agreement/disagreement on a five-point scale. For question Q10 (“Do you think that climate service should include the following tasks or activities?”), a total of 15 different future climate service tasks and activities were proposed. The total number of respondents was 2,486 for Q8 and 2,192 for Q10. We used a five-level Likert scale, meaning that for each proposed statement, the respondents could select between five alternatives [from 1 (fully disagree) to 5 (fully agree)] or skip. Note that in this paper we use a reversed scale compared to the original one in the supplemental information (see the section labeled “Reanalysis user and application survey”). For each proposition, we calculated the mean and standard deviation across ALL and separately for the four subgroups (WAT, AGR, FOR, and ENE): the higher the mean, the higher level of agreement. For each statement, the statistical significance of the difference between the resulting mean and the median Likert item 3 was assessed using a two-sided one-sample Student’s t test.

To test for correlations between the answers of the subgroups, principal component (PC) analysis (PCA) was performed using the RDA function from the Vegan package (Oksanen et al. 2008) in R (R Development Core Team 2013). This technique reduces the dimensionality in a dataset, searching for an arrangement that explains the most variation in the data. The best linear fit for each subgroup to the PCA ordination scores was determined, testing the significance of the fit using a permutation approach (implemented by the envfit function). For the analysis, the subgroups were coded as dummy variables (1 indicates “belongs to group”; 0 indicates “does not belong to group”).

To obtain further background information about the respondents, they were asked to state whether they use reanalysis data, and if so, they were invited to select all the reanalysis datasets that applied. Essential climate variables (ECV) were considered. Respondents were also asked about applications and methods used.

Analyses of the respondents’ opinions and needs. The main aim of the survey was to identify awareness and needs of the respondents in regard to reanalyses (Q7–Q9, Q11) and their perceptions of climate services (Q10 and Q11; see the supplemental information, section labeled “Reanalysis user and application survey”). For question Q8 (“Regarding the characteristics of reanalysis data, would you say that...?”), a total of 23 statements were proposed, asking users to express their level of agreement/disagreement on a five-point scale. For question Q10 (“Do you think that climate service should include the following tasks or activities?”), a total of 15 different future climate service tasks and activities were proposed. The total number of respondents was 2,486 for Q8 and 2,192 for Q10. We used a five-level Likert scale, meaning that for each proposed statement, the respondents could select between five alternatives [from 1 (fully disagree) to 5 (fully agree)] or skip. Note that in this paper we use a reversed scale compared to the original one in the supplemental information (see the section labeled “Reanalysis user and application survey”). For each proposition, we calculated the mean and standard deviation across ALL and separately for the four subgroups (WAT, AGR, FOR, and ENE): the higher the mean, the higher level of agreement. For each statement, the statistical significance of the difference between the resulting mean and the median Likert item 3 was assessed using a two-sided one-sample Student’s t test.

To test for correlations between the answers of the subgroups, principal component (PC) analysis (PCA) was performed using the RDA function from the Vegan package (Oksanen et al. 2008) in R (R Development Core Team 2013). This technique reduces the dimensionality in a dataset, searching for an arrangement that explains the most variation in the data. The best linear fit for each subgroup to the PCA ordination scores was determined, testing the significance of the fit using a permutation approach (implemented by the envfit function). For the analysis, the subgroups were coded as dummy variables (1 indicates “belongs to group”; 0 indicates “does not belong to group”).

Free-form comments concerning reanalysis datasets (Q9) and future climate services (Q11) were analyzed only for the four selected subgroups. The share of respondents leaving free comments for Q9 was roughly one-third (from 34 respondents in FOR to 97 respondents in ENE) and less than one-fifth (from 21 respondents in FOR to 37 respondents in ENE) for Q11.
After filtering out vague responses and answers of the type “no comment,” the number of remaining responses decreased further. Two reviewers investigated the responses by reading and clustered those with clear suggestions and opinions. Because similar topics arose both in Q9 and Q11, the responses for these two survey points were merged. Because of the very subjective nature of their analysis, the free comments can only be handled as a presentation of a variety of opinions about the users’ needs concerning reanalyses and climate services.

RESULTS. Demographics, scientific discipline, and regional focus of work. Based on CON provided by 907 (35%) out of 2,578 respondents, people from at least 97 countries took part in the survey. The highest number (153) of CON came from China, second (81) from India, and third (71) from the United States. At least 30 contacts were also obtained from Germany, France, Italy, Spain, and Indonesia (Table S1). Education and public research and development (R&D) were among the most important fields of work for the respondents in China, India, Japan, and the United States. The private sector was represented especially by the United States, France, Germany, India, and Italy (not shown).

Considering ALL, WAT, AGR, and FOR, the majority (80%) of respondents were from the education or public R&D sectors. ENE was an exception in that the private sector was as numerous as the public R&D sector (85 respondents or 34%; Fig. 2). Respondents from public sector operations other than R&D, from international agencies or organizations, and from the non-profit sector appeared in the minority in the four subgroups.

We compared the respondents’ sectorial distributions before and after 21 January 2014, the date of the first advertisements that were followed by the sharp increase in the number of responses (Fig. 1). No statistically significant difference was found (chi-squared test). This suggests that e-mailing by NOAA and/or ECMWF did not bias the demographical orientation of respondents, at least not for the distribution of sectors of work.

The two most prevalent fields or subjects of work for ALL were climate and weather, the former occurring among 73% of ALL and the latter among 47% of ALL (Table 1). Only 18% of ALL declared that their work involved neither. The subgroups appeared in the seventh position for ENE (10% of ALL), ninth position for WAT (7%), twelfth for AGR (5%), and thirteenth for FOR (4%). Because the survey invited respondents to choose all the fields that applied, these groups were partially overlapping. AGR and FOR had the largest proportion of common respondents.

The respondents reported geographical interest for the whole globe, Europe, and Asia, which were included in the six most popular regions for ALL and the four subgroups. The most common regional focus of work for the four subgroups was Europe, especially for ENE (50%) but also for WAT, AGR, and FOR (33%). For ALL, the whole globe was the most typical

<table>
<thead>
<tr>
<th>Field</th>
<th>Percentage of respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>125</td>
</tr>
<tr>
<td>Weather</td>
<td>88</td>
</tr>
<tr>
<td>Oceans, seas</td>
<td>44</td>
</tr>
<tr>
<td>Other aspects of atmosphere</td>
<td>38</td>
</tr>
<tr>
<td>Air quality</td>
<td>33</td>
</tr>
<tr>
<td>Snow, ice</td>
<td>30</td>
</tr>
<tr>
<td>Energy</td>
<td>28</td>
</tr>
<tr>
<td>Geophysics/chemistry</td>
<td>74</td>
</tr>
<tr>
<td>Water management</td>
<td>72</td>
</tr>
<tr>
<td>Ecosystems, biodiversity</td>
<td>76</td>
</tr>
<tr>
<td>Geography</td>
<td>46</td>
</tr>
<tr>
<td>Agriculture, food production</td>
<td>126</td>
</tr>
<tr>
<td>Forestry</td>
<td>43</td>
</tr>
<tr>
<td>Safety</td>
<td>26</td>
</tr>
<tr>
<td>Flooding of coastal areas</td>
<td>24</td>
</tr>
<tr>
<td>Transport</td>
<td>24</td>
</tr>
<tr>
<td>Geoinformatics</td>
<td>22</td>
</tr>
<tr>
<td>Well being</td>
<td>21</td>
</tr>
<tr>
<td>Industry</td>
<td>21</td>
</tr>
<tr>
<td>Insurance</td>
<td>20</td>
</tr>
<tr>
<td>Economics</td>
<td>19</td>
</tr>
<tr>
<td>Geology</td>
<td>15</td>
</tr>
<tr>
<td>Construction and engineering</td>
<td>12</td>
</tr>
<tr>
<td>Communication</td>
<td>10</td>
</tr>
<tr>
<td>Urban or other design</td>
<td>9</td>
</tr>
<tr>
<td>Tourism</td>
<td>8</td>
</tr>
<tr>
<td>Other social aspects</td>
<td>7</td>
</tr>
<tr>
<td>Indigenous peoples issues</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1. Work focus distribution of ALL and the four subgroups. The respondents were asked to choose all that apply: arrow up indicates the highest percentage (67%–100%) of responses, arrow right indicates the medium share (34%–66%), and arrow down indicates the lowest share (1%–33%) of responses within each main field of work.
regional focus of work (32% of the respondents). Also Africa was included in the six most popular regions for ALL and the four subgroups. In addition to these, ALL concentrated also on the oceans [Pacific Ocean (9%) being fourth and “Mostly oceans” (8%) being sixth position]. AGR focused on continents with developing countries [International Monetary Fund (IMF) definition], with Africa (27%) being in second and South America (20%) being in fourth position; FOR focused on continents [“Mostly continents” (23%) being in fourth position]; and WAT (19%) and ENE (12%) focused on specific countries (“Specific countries” being in fourth position for both of them).

Reanalysis products used. Among ALL respondents, the largest counts for the use of different atmospheric reanalyses were for ERA-Interim (2,049/2,578; 79%); ERA-40 (1,325; 51%); National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalyses (R1; 1,100; 39%); NCEP–DOE Atmospheric Model Intercomparison Project phase 2 (AMIP-II) reanalysis (R2; 592; 23%); and NCEP [Climate Forecast System Reanalysis (CFSR; 572; 22%; Table 2]. ERA-Interim alone was used by 391 respondents (15% of ALL), whereas 241 respondents (9%) did not use any atmospheric reanalysis by ECMWF and 90 (3.5%) declared not using any reanalysis products at all. For a more complete list of atmospheric and oceanic reanalysis datasets used by ALL respondents, see Gregow et al. (2015).

We also investigated usage counts for each of the four subgroups (Table 2). For subgroups WAT and AGR, ERA-Interim and ERA-40 were the most used reanalyses and NCEP reanalyses were the second most used. But for FOR and ENE, only ERA-Interim was clearly most used, whereas the NCEP reanalyses and ERA-40 were the second most used. Additionally, the proportion of ENE using National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA) as well as the proportion of ENE and FOR using NCEP–DOE AMIP-II (R2) was rather high.

User awareness and needs in regard to use of reanalyses. Regarding the statements about the characteristics of reanalysis data, the mean scores given by ALL ranged from 3.1 to 3.9, and the standard deviations ranged from 0.9 to 1.3 (Table 3). The average across all the statements was 3.5, and the standard deviation of the mean scores was 0.3. The statements were phrased such that higher scores meant greater satisfaction with the characteristic, and lower scores meant more dissatisfaction.

When considering ALL, the propositions invariably obtained a score that was statistically significantly higher than the midpoint of the Likert scale (Table 3). This implies that the respondents were satisfied rather than unhappy with the characteristics of reanalysis data. On average, the respondents most strongly agreed with the proposition that “The data is easy to access.” On the other hand, the propositions having the lowest statistical significance (two-sided p value between 0.002 and 0.01) and thereby exhibiting the least satisfaction were “The uncertainties are well characterized,” “Plentiful training material is available on the web,” and “I know how much the temporal true (feature) resolution differs from the nominal resolution in time.” It is noteworthy that these proportions, together with a few other statements, had a high portion (50%–60%) of respondents being “in between” or not answering at all (Fig. 3). This suggests that the issues in question may have been unimportant or unclear for many respondents. The results can be taken as an indication of the areas where there is need for future reanalysis development and increasing the awareness of the user community.

When considering the four subgroups separately, the need for further work related to the characteristics of

Table 2. Atmospheric reanalysis datasets used by the respondents. Arrow codes are analyzed separately for ALL and each subgroup. The arrow codes are explained in Table 1.
reanalysis data and user awareness became even more obvious. Now several statements failed to achieve a statistically significantly score higher than 3 (Table 3). For example, the ENE respondents would appreciate, more clearly than ALL, improvements in spatiotemporal scales and more information about observation input to reanalysis. AGR and FOR shared the view with ENE that the data policy is somewhat restrictive and could be made easier and that the reanalysis data tend to become available too late. The WAT respondents especially wish for higher horizontal nominal (gridcell size) resolution and smaller biases compared with observations and tend to be worried about whether time-varying biases make the data too unstable for their needs.

In this context, it should be noted that survey respondents most commonly used reanalysis data for applications such as studies of atmospheric dynamics and physics and atmospheric and climate modeling (Table S2). The subgroups of WAT, AGR, FOR, and ENE also indicated time series analysis among the most common applications. ENE additionally uses reanalyses for resource assessment of renewable energies, WAT and AGR for studying climate change impacts, and WAT also for climate change detection.

### Table 3. Opinions of the respondents regarding the characteristics of reanalysis data. Column 1 lists the statements; column 2 shows the mean scores according to ALL (1 = fully disagree, 5 = fully agree); column 3 shows the standard deviations of scores according to ALL; and columns 4–8 show the statistical significance of the difference from the midpoint of the Likert item 3 separately for ALL (2,486 respondents to Q8), WAT (165), AGR (128), FOR (105), and ENE (239). The following notation is used: * indicates 0.05 < p ≤ 0.01, ** indicates 0.01 < p ≤ 0.001, and *** indicates p < 0.001.

<table>
<thead>
<tr>
<th>Statement about reanalysis data</th>
<th>ALL mean</th>
<th>ALL std dev</th>
<th>ALL p</th>
<th>WAT p</th>
<th>AGR p</th>
<th>FOR p</th>
<th>ENE p</th>
</tr>
</thead>
<tbody>
<tr>
<td>The data are easy to access.</td>
<td>3.9</td>
<td>1.2</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>The data policy is NOT too strict.</td>
<td>3.3</td>
<td>1.3</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>The file sizes are NOT too large to work with.</td>
<td>3.4</td>
<td>1.2</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>The data can be imported easily by my software application.</td>
<td>3.7</td>
<td>1.2</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>The horizontal nominal (grid cell size) resolution is adequate.</td>
<td>3.4</td>
<td>1.2</td>
<td>***</td>
<td>—</td>
<td>***</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>The vertical nominal (grid cell size) resolution is adequate.</td>
<td>3.6</td>
<td>1.1</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>The temporal nominal resolution is adequate.</td>
<td>3.6</td>
<td>1.2</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>For the climate variables I need, I know how much their spatial true (feature) resolution differs from the nominal resolution.</td>
<td>3.1</td>
<td>1.2</td>
<td>***</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td>—</td>
</tr>
<tr>
<td>I know how much the temporal true (feature) resolution differs from the nominal resolution in time.</td>
<td>3.1</td>
<td>1.2</td>
<td>***</td>
<td>—</td>
<td>*</td>
<td>***</td>
<td>—</td>
</tr>
<tr>
<td>The spatiotemporal scales that I need are well represented.</td>
<td>3.4</td>
<td>1.1</td>
<td>***</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td>—</td>
</tr>
<tr>
<td>The time period covers my interests.</td>
<td>3.8</td>
<td>1.2</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>The data are consistent between the variables.</td>
<td>3.8</td>
<td>1.0</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>The general quality is good enough for my needs.</td>
<td>3.8</td>
<td>1.0</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>The biases compared with observations are small enough.</td>
<td>3.3</td>
<td>0.9</td>
<td>***</td>
<td>—</td>
<td>***</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>Time-varying biases DO NOT make the data too unstable for my needs.</td>
<td>3.2</td>
<td>1.0</td>
<td>***</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>The temporal continuity is adequate.</td>
<td>3.7</td>
<td>1.0</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>The uncertainties are well characterized.</td>
<td>3.1</td>
<td>1.0</td>
<td>***</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>The observation input to reanalysis is clearly explained.</td>
<td>3.1</td>
<td>1.1</td>
<td>***</td>
<td>—</td>
<td>*</td>
<td>***</td>
<td>—</td>
</tr>
<tr>
<td>I know enough to work with the data.</td>
<td>3.6</td>
<td>1.0</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>The data DO NOT tend to become available too late for my needs.</td>
<td>3.4</td>
<td>1.2</td>
<td>***</td>
<td>*</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Plentiful training material is available on the web.</td>
<td>3.1</td>
<td>1.0</td>
<td>***</td>
<td>—</td>
<td>*</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>The literature provides good information.</td>
<td>3.4</td>
<td>1.0</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Websites provide good information.</td>
<td>3.5</td>
<td>1.1</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>
The data is easy to access
The time period covers my interests
The data are consistent between the variables
The general quality is good enough for my needs
The temporal continuity is adequate
The data can be imported easily by my software application
I know enough to work with the data
The temporal nominal resolution is adequate
The vertical nominal (grid cell size) resolution is adequate
Websites provide good information
The spatio-temporal scales that I need are well represented
The file sizes are not too large to work with
The literature provides good information
The horizontal nominal (grid cell size) resolution is adequate
The data do not tend to become available too late for my needs
The data policy is not too strict
The biases compared with observations are small enough
Time-varying biases do not make the data too unstable for my needs
For the climate variables I need, I know how much their spatial true is
I know how much the temporal true (feature) resolution differs from
The observation input to reanalysis are clearly explained
Plentiful training material is available on the web
The uncertainties are well characterized

Fig. 3. Distribution (%) of agreement with regard to propositions about the characteristics of reanalysis data. The total number of people responding to one or several statements was 2,486. The propositions have been sorted according to their mean score (see Table 3).

Fig. 4. PCA showing the relative similarity of the answers for (a) Q8 (“Regarding the characteristics of Reanalysis data...”) and (b) Q10 (“Regarding future of climate services...”). The abbreviation of the sectors and their position in the ordinations indicate the linear correlation with the answers (distances are scaled by the strength of correlation). The solid gray areas represent answers regarding similar topics (italic font). The sectors with black fonts are not significantly related to the ordination (p > 0.05; tested with 1,000 random permutation of the data). Sectors are abbreviated as follows: weather (WEA), climate (CLI), air quality (AQU), other aspects of atmosphere (OTH), oceans and sea (OCE), freshwater resources and management (WAT), snow and ice (SMW), agriculture and food production (AGR), forests (FOR), ecosystems and biodiversity (ECO), erosion and flooding of coastal areas (ERO), energy (ENE), industry (IND), transportation (TRA), economics (ECN), insurance (INS), architecture (ARC), construction and municipal engineering (CON), health and human well-being (HEA), tourist and recreation (TOU), safety and security (SAF), indigenous peoples issues (IND), geophysics and geochemistry (CPH), geoinformatics (GIS), geology (GEL), and geography (GEG).
A few percent (3.5%) of ALL had not used reanalysis products at all but applied climate data from other sources such as in situ, in situ gridded, or satellite data (Tables S2 and S3). It appeared that they slightly more commonly disagreed with the statements “The data can be imported easily by my software application,” “The data is easy to access,” “I know enough to work with the data,” “The file sizes are not too large to work with,” “Time-varying biases do not make the data too unstable for my needs,” and “The general quality is good enough for my needs.”

The principal component analysis revealed that the majority of the variation in the data can be suppressed into the first two components PC1 and PC2 (Tables S4 and S5). With regard to Q8, the two components PC1 (27%) and PC2 (12%) explain, in total, 39% of the variance. The two highest component loadings are temporal nominal resolution and general quality for PC1 and timely availability of the data and data policy for PC2. The Q10 responses regarding the opinions of future climate services can be largely described by PC1, which explains 56% of the variance. The component loadings for PC1 are almost invariant, with the detection of climate change and production of long-term climate projections representing only slightly higher loadings than the other components.

Based on the principal component analysis, the answers can roughly be grouped to concern “Quality and scale,” “Metadata,” and “Data policy” issues (Fig. 4a). Concerning free-form comments about reanalysis data, the largest share of responses dealt with data access, formats, and quality. Many users hoped for earlier availability of data (Table 4).

### Respondents’ opinions in regard to future climate services.
All of the 15 postulated climate service tasks and activities received, on average, positive interest from the survey respondents, as was shown by the PC analysis. The mean scores given by ALL ranged from 3.6 to 4.2 (Table 5) with a mean score of 3.8 (standard deviation of 0.2). For both ALL and the four subgroups, the mean score of each proposition was statistically significantly higher than the midpoint of the Likert scale 3. On the other hand, none of the activities gained a total consensus, as 7%–15% of the respondents did not think that these should be included in future climate services (Fig. 5). The strongest support was expressed by ALL for...

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<table>
<thead>
<tr>
<th>Table 4. Free-form comments concerning use of reanalyses. Two reviewers read through the responses and categorized the needs of users independently.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reviewer A</strong></td>
</tr>
<tr>
<td>1) The largest share of responses dealt with data access, formats, and quality.</td>
</tr>
<tr>
<td>2) Many users hoped for earlier availability of data.</td>
</tr>
<tr>
<td>3) Clear representation of uncertainties in the data was considered important.</td>
</tr>
<tr>
<td>4) Be able to compare reanalyses; users would like to have training and more online plotting tools.</td>
</tr>
<tr>
<td>5) Summer schools and workshops were mentioned and there was a wish that these training could be given in native languages as well.</td>
</tr>
<tr>
<td>6) There was an overall recommendation to make the access and downloading of data as easy as possible. Suggested popular data formats included NetCDF.</td>
</tr>
<tr>
<td>7) There was a wish to have scripts available to help downloading and to have Windows and OPeNDAP compatibility. Open and free access was also desired.</td>
</tr>
<tr>
<td><strong>Reviewer B</strong></td>
</tr>
<tr>
<td>1) Improve resolution and provide longer time series (146).</td>
</tr>
<tr>
<td>2) Consultation, training, and tutorials for, for example, guiding in search of data (96).</td>
</tr>
<tr>
<td>3) More parameters that are currently not available (85) (missing data)</td>
</tr>
<tr>
<td>4) Data costs were not wanted, and data were desired to be more easily available (64).</td>
</tr>
<tr>
<td>5) Data format was considered difficult and suggestions were given (48).</td>
</tr>
<tr>
<td>6) Slow downloading bothered (39).</td>
</tr>
<tr>
<td>7) Near-real-time or real-time updates were desired (30).</td>
</tr>
<tr>
<td>8) Data quality (20).</td>
</tr>
<tr>
<td>9) Web page updates to become more user-friendly (14).</td>
</tr>
</tbody>
</table>
“Interpolation and production of gridded datasets based on observations,” “Provision of statistics based on observations,” and “Homogenization of weather station data.”

It appeared that the four subgroups in general gave somewhat higher scores for the proposed climate service tasks and activities than the respondents outside these subgroups (not shown). The three most consensual activities were the same (even with varying order) in ENE, FOR, and WAT as in ALL (Table 5). Regarding proposed activities outside the top three, FOR valued “Statistical impact analyses for improving weather warnings and their criteria,” “Climate change impact consultancy for decision makers,” and “Production of long-term climate projections” clearly higher in their priority list than ALL did. AGR and WAT gave, in turn, more emphasis on “Applied weather and climate research for impact assessment,” and ENE gave more emphasis on “24/7 updates, in the internet, of statistics of weather and climate” than ALL. Despite these differences, the principal component analysis for Q10 revealed clear similarities in the answers. Three clusters could be identified: “Climate change and long-term forecasts,” “Bulletins and statistics,” and “Observations and verification” (Fig. 4b).

The 2,488 respondents that had used reanalysis for at least one geophysical variable exhibited more distinct polarity in their opinions on the issues of Table 5: the fraction answering “in between 3” or not at all was on average 44%, whereas it was 60% for those who had not used reanalysis. In general, the reanalysis users agreed more strongly in all cases: their scores were 5%–22% higher than those of the others. The largest difference in response to individual questions was that the people using reanalysis were more in favor (22%) of the “Provision of statistics based on observations,” whereas the others were more uncertain (22%). Other stronger differences in opinions for or against were that the reanalysis users agreed more strongly about “Monthly forecasting and verification” (20%), “Homogenization of weather station data” (19%), and “Interpolation and production of gridded datasets based on observations” (18%). Otherwise the differences in single questions (other than in between) were at most 15%. On average, the reanalysis users agreed more by 13% and disagreed more by 2.6%. The maximum difference in the average scores of individual answers was only 0.32.

<table>
<thead>
<tr>
<th>Statement about climate services</th>
<th>ALL mean</th>
<th>ALL std dev</th>
<th>ALL p</th>
<th>WAT Δ</th>
<th>AGR Δ</th>
<th>FOR Δ</th>
<th>ENE Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpolation and production of gridded datasets based on observations.</td>
<td>4.2</td>
<td>1.1</td>
<td>***</td>
<td>−1</td>
<td>−3</td>
<td>0</td>
<td>−1</td>
</tr>
<tr>
<td>Provision of statistics based on observations.</td>
<td>4.1</td>
<td>1.1</td>
<td>***</td>
<td>−1</td>
<td>0</td>
<td>0</td>
<td>−1</td>
</tr>
<tr>
<td>Homogenization of weather station data.</td>
<td>4.1</td>
<td>1.1</td>
<td>***</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Research and communication of climate change uncertainties.</td>
<td>4.0</td>
<td>1.1</td>
<td>***</td>
<td>0</td>
<td>−3</td>
<td>−8</td>
<td>0</td>
</tr>
<tr>
<td>Monthly forecasting and verification.</td>
<td>3.9</td>
<td>1.1</td>
<td>***</td>
<td>−2</td>
<td>0</td>
<td>−1</td>
<td>0</td>
</tr>
<tr>
<td>Detection of climate change.</td>
<td>3.9</td>
<td>1.1</td>
<td>***</td>
<td>1</td>
<td>−3</td>
<td>−3</td>
<td>0</td>
</tr>
<tr>
<td>Seasonal forecasting and verification.</td>
<td>3.9</td>
<td>1.2</td>
<td>***</td>
<td>−1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Production of long-term climate projections.</td>
<td>3.8</td>
<td>1.2</td>
<td>***</td>
<td>−1</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Applied weather and climate research for impact assessment.</td>
<td>3.8</td>
<td>1.1</td>
<td>***</td>
<td>3</td>
<td>6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Provision of statements describing past weather events.</td>
<td>3.8</td>
<td>1.1</td>
<td>***</td>
<td>−1</td>
<td>−1</td>
<td>−1</td>
<td>0</td>
</tr>
<tr>
<td>Attribution of climate change.</td>
<td>3.7</td>
<td>1.2</td>
<td>***</td>
<td>1</td>
<td>−2</td>
<td>−2</td>
<td>−1</td>
</tr>
<tr>
<td>Statistical impact analyses for improving weather warnings and their criteria.</td>
<td>3.7</td>
<td>1.1</td>
<td>***</td>
<td>0</td>
<td>2</td>
<td>8</td>
<td>−1</td>
</tr>
<tr>
<td>Climate watch bulletins.</td>
<td>3.6</td>
<td>1.1</td>
<td>***</td>
<td>−1</td>
<td>−2</td>
<td>−2</td>
<td>−2</td>
</tr>
<tr>
<td>24/7 updates, on the Internet, of statistics of weather and climate.</td>
<td>3.6</td>
<td>1.2</td>
<td>***</td>
<td>−1</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Climate change impact consultancy for decision-makers.</td>
<td>3.6</td>
<td>1.2</td>
<td>***</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
Given the potential for sampling bias arising from the high proportion (91%) of responses from ECMWF reanalysis users, we make no claim that the opinions expressed by survey respondents on climate service activities should be regarded as fully representative of the wider and time-evolving climate service community. We would, however, be pleased to contribute our sample to more comprehensive compilations of community opinion.

CONCLUSIONS. This paper reports on a survey designed to identify the obstacles to the use of reanalysis in support of future climate services. The results are based on a worldwide survey conducted in winter 2013/14. The contextual background of the survey respondents is indicated by their sector, field of work, and region of focus. The major sectors were public R&D (1,170 out of 2,578 respondents; or 45%) and education (941; 37%), and only a minority was from the private sector (189; 7%). Similar proportions were reported for three of the four selected subgroups: WAT, AGR, and FOR. These consisted of respondents who declared their main field of work to be freshwater resources and management, agriculture and food production, or forests. In contrast, approximately one-third of the respondents from the energy sector (ENE) represented the private sector.

The results from ALL indicated that reanalyses are used in various applications, for instance, when studying atmospheric dynamics and physics and/or working on atmospheric and climate modeling. The four subgroups also use reanalyses for time series analyses (WAT, AGR, FOR, ENE), for studying climate change impacts (WAT and AGR), for climate change detection (WAT), and for resource assessment for renewable energies (ENE). ALL particularly wish for better characterization and communication of the uncertainties and limitations of the reanalysis data. In addition, they desire less restrictive data policy, more help and information on websites, and faster updates and release of data. ENE and WAT respondents additionally wish for higher temporal and spatial resolution, and WAT also wishes for smaller biases. All of these points are pertinent considerations in the development of the Copernicus Climate Change Service (C3S) and the Global Framework for Climate Services (GFCS).

The respondents acknowledge that they need support to better understand the reanalyses. Summer schools and workshops were desired in the free-form answers by the four subgroups, who also expressed a need to have more ready-made scripts and tools to help downloading. If such support services were to be provided in native languages, it would be very much appreciated at least by some of the respondents. Reanalysis uptake as part of the future climate services could thus be increased by capacity building and by enhancing the outreach and dissemination activities. Some aspects of the capacity building would need to be undertaken by the data provider community, while other aspects would need to be undertaken by the data user community. We note the potential for different national bodies to provide native language

![Fig. 5. Distribution (%) of agreement with regard to propositions about future climate service activities. The total number of people responding to one or several statements was 2,192. The propositions have been sorted according to their mean score (see Table 5).](image-url)
support and encourage them to engage in the planning and implementation of the C3S outreach and dissemination (OD) as well as the GFCS capacity building (CB) future activities. Capacity building to characterize and understand dataset uncertainties, including the development of analytical techniques and provision of data evaluation tools, is of strategic importance and will require sustained effort.

Survey responses expressing interest in the delivery of tailored monthly to seasonal-scale forecasting for agriculture applications could be of interest to the research, modeling, and prediction (RMP) pillar of the GFCS. A similar conclusion concerning agriculture (and food production) was presented by Tall et al. (2014) who stated that the components within a climate service would need a seamless suite of forecast (subdaily to at least seasonal), advisory, and early warning products to help farmers manage evolving risks during the growing season with large enough lead time.

We caution against overinterpreting these results, particularly where sampling and response biases may affect representativeness; 1,332 (52%) responses came within five days after NOAA and ECMWF had advertised the survey on 21–22 January 2014, and an additional 860 (33%) responses arrived after the second e-mailing by ECMWF on 24 February 2014. Respondents using non-ECMWF reanalyses amounted to 1,010 (39%) using NCEP–NCAR (R1), 592 (23%) using NCEP–DOE AMPI-II (R2), 572 (22%) using NCEP (CFSR), 349 (14%) using Japan Meteorological Agency (JMA) Japanese 25-year Reanalysis Project (JRA-25), and 60 (2%) using the Japan Meteorological Agency Climate Data Assimilation System (ICDAS). Their responses allow identification of developments that would increase the user uptake of reanalyses more generally.

Counts of using various reanalysis datasets are of course influenced by many factors, including the population we were able to reach in the survey and the time that respondents had to familiarize themselves with the datasets, so it is not surprising that relatively new reanalyses such as JMA's JCDAS have lower counts. Usage counts are arguably most informative when tracked over time in a succession of surveys.

Existing reanalysis users represent one portion of the future climate services community that is itself anticipated to grow as the availability of climate information improves and new applications are developed. We recommend that further steps be taken to ascertain more comprehensively the needs of the wider climate services community and offer our results as a contribution to the broader effort. The responses of this survey are most suited to studies of the characteristics and use of reanalysis data. In the future, our investigations will concentrate on the differences between users' views of the various reanalyses and datasets, user applications, and fields of work such as safety and insurance.

ACKNOWLEDGMENTS. This work was financially supported by the EU FP7 CORE-CLIMAX project. Satu Kekki is thanked for the technical design of the Webropol survey. We thank Carsten Maass from ECMWF for arranging e-mailing about 24,000 ECMWF users, Karolin Eichler from WMO for helping distribute the survey to the WMO regional offices, Gil Compo from CIIRES for advertising the survey in the United States, and Shinya Kobayashi for advertising the survey to users of JMA reanalyses. We are very grateful to all of the respondents for giving their time to take part in the survey. Prof. Ari Laaksonen is thanked for commenting on the manuscript. We are thankful for the two referees for their valuable comments that helped us improve the paper.

REFERENCES


——, M. Balmaseda, G. Balsamo, R. Engelen, A. J. Simmons, and J.-N. Thépaut, 2014: Toward a consistent


**EYEWITNESS**

Evolution of the Atmospheric Sciences

by ROBERT G. FLEAGLE

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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),
The linkage of the occurrence probability of continental-scale cold-air outbreaks to the amount of air mass transported into the polar stratosphere suggests that it is feasible to predict them 1 month in advance.

Past studies have linked the weakening of the stratospheric polar vortex or the negative phase of the northern annular mode (NAM) to episodes of extreme cold events that occur later in the mid-latitudes (Thompson and Wallace 2001; Baldwin and Dunkerton 2001; Thompson et al. 2002; Cai 2003; Kolstad et al. 2010; Mitchell et al. 2013; Kidston et al. 2015). The presence of the NAM variability in the lower stratosphere also provides enhanced predictability of the Arctic Oscillation (AO) or the tropospheric NAM variability (Baldwin et al. 2003; Kuroda 2008; Douville 2009; Gerber et al. 2009; Hardiman et al. 2011; Smith et al. 2012; Sigmund et al. 2013; Tripathi et al. 2014). This enhanced predictability has been attributed to the dynamical coupling between the stratosphere and troposphere via 1) systematic downward propagation of geopotential height and zonal wind anomalies in the extratropics (Kodera and Kuroda 1990; Baldwin and Kuroda 1999; Baldwin and Dunkerton 2001; Cai and Ren 2007; Ren and Cai 2007), 2) the delayed feedbacks of the stratosphere to the upward propagation of tropospheric Rossby waves (Hartley et al. 1998; Limpavusan and Hartmann 2000; Ambaum and Hoskins 2002; Polvani and Waugh 2004; Kuroda 2008), 3) the downward control principle (Haynes et al. 1991) and with transient eddy feedbacks (Song and Robinson 2004), 4) the reflection of planetary waves (Perlwitz and Harnik 2003), and 5) the invertibility principle of potential vorticity (Hartley et al. 1998). Readers may consult the monumental review papers by Holton et al. (1995), Shepherd (2002), and Haynes (2005), and the references therein, about the two-way coupling mechanisms between the stratosphere and troposphere in the extratropics. The stratospheric connection to the AO and the associated extreme weather events have been recognized as a new opportunity for intraseasonal climate predictions during winter seasons since the stratospheric signal provides long-lead precursor information (0–60 days) to anomalous surface regimes (Baldwin and Dunkerton 2001; Thompson and Wallace 2001; Baldwin et al. 2003; Polvani and Waugh 2004).

The conventional wisdom is that the stratosphere is more predictable than the troposphere because of its longer persistent time scale from the dominance of the quasi-stationary planetary-scale Rossby waves over the fast-moving synoptic-scale waves. With more satellite data in the stratosphere to assimilate and increased vertical resolution, we now have the capability to use numerical weather prediction (NWP).
Motivated by the work cited above and referenced therein, we here propose a hybrid (dynamical plus statistical) paradigm for predicting the occurrence of individual continental-scale cold-air outbreaks (CAOs) in winter at the subseasonal range (0–30 days). As outlined in Fig. 1, the proposed hybrid paradigm is built on the following two premises: 1) the existence of robust diagnostic relationships between one or more indices that describe stratospheric circulation variability and indices of continental-scale CAOs at the surface and 2) the ability of operational models to predict the stratospheric indices used in the first premise 0–30 days in advance. Note that the temporal lead information in such a hybrid paradigm comes from dynamics/physics-based state-of-the-art operational models and the existence of precursor information in the statistical diagnostic component is not required. Therefore, the choice of such circulation indices is key for taking advantage of models’ useful skill in the subseasonal range.

In the next section, we will discuss the rationales for the choices of the circulation indices in our deliberation on the feasibility of the proposed hybrid paradigm. The data, methods, and definitions section describes briefly the methods for deriving the circulation and CAO indices from standard outputs of operational models and historical data. The section on the association of CAOs with the strengthening of mass transport into the polar stratosphere is devoted to establishing the statistical relationship between the circulation and CAO indices. In the section on skill evaluations of forecasts for the ST60N, CNA, and CEA indices during the 2013/14 winter, we present evidence showing that the NCEP Climate Forecast System, version 2 (CFSv2; Saha et al. 2014) indeed possesses useful skill in predicting the circulation index at a range longer than 2 weeks in advance. The following section outlines a prototype procedure for real-time subseasonal forecasts of CAOs by combining the results presented earlier. The concluding remarks are provided in the final section of the paper. Detailed information on the skill evaluation and additional supporting evidences are provided in the online supplement to this paper (available online at http://dx.doi.org/10.1175/BAMS-D-14-00287.2).

**RATIONALES FOR THE choisE OF CIRCULATION INDICES.** As reported in the literature (e.g., the references cited earlier), many stratospheric circulation indices, such as the northern annular mode (NAM), zonal mean zonal wind, polar vortex oscillation, eddy poleward heat flux (or the vertical component of the Eliassen–Palm flux), and streamfunction of the residual circulation

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inferred from the downward control principle, may bear long-lead precursor information (0–60 days) for surface temperature anomalies. Such long-lead information has been utilized in statistical models for predicting monthly or seasonal mean surface temperature anomalies (e.g., Christiansen 2005; Siegmund 2005; Karpechko 2015). However, to the best of our knowledge, such statistical long-lead information has not been utilized for subseasonal forecasts of individual CAOs in a real-time (or operational) setting.

Because the temporal lead information for subseasonal forecasts of individual continental-scale CAOs in the hybrid paradigm comes from operational models’ forecasts, we need to consider the following two requirements in selecting circulation indices: 1) they are predictable by operational models with a useful level of skill at a lead time longer than 2 weeks and 2) they are associated with dynamical processes that are physically responsible for individual CAOs. The second requirement above allows us to have a built-in causal relation in the statistical diagnostic component that links individual CAOs to circulation indices. Unlike monthly or seasonal mean temperature anomalies, the day-to-day variability of temperature anomalies is driven mainly by weather systems.

It has been shown in Yu et al. (2015a) that the timing of CAOs in midlatitudes is associated with the strengthening of equatorward cold airmass transport in the lower troposphere and the latter is nearly synchronized with the poleward warm-air transport in the upper atmosphere (including the stratosphere) into the polar region. Yu et al. (2015c) further showed that the anomalous intensification of surface weather systems that are responsible for CAOs is linked to the strengthening of the poleward warm-air transport in the upper atmosphere. The mechanism for the simultaneous poleward mass flux in upper-isentropic layers and equatorward mass flux below in the extratropics has been uniquely attributed to the dominance of westward-titled baroclinic waves (Johnson 1989). As a result of the hydrostatic and (quasi-) geostrophic balance, westward-tilted baroclinic waves always have a net poleward mass transport in upper levels and equatorward mass transport in lower levels. Intensification of westward-tilted waves results in a near-simultaneous increase in both the poleward mass transport into the polar region aloft and the equatorward discharge of the cold polar air mass in the lower troposphere, responsible for CAOs in the midlatitudes. Deep and large-amplitude baroclinic waves are capable of driving a strong meridional mass circulation that is connected to the stratosphere. Therefore, the stronger poleward mass transport in the extratropical stratosphere can be a robust indicator of the equatorward mass transport out of the

Fig. 1. Schematic showing the main components and the process flow of the proposed hybrid paradigm for subseasonal forecasts of continental-scale CAOs in the midlatitudes.
polar region in the lower troposphere [see sections 7 and 8 in Cai and Ren (2007) for the observational evidence]. This is the basis for the existence of the physical causal relationship between the mass circulation in the stratosphere and CAOs, which can be used as the statistical component of the hybrid paradigm for subseasonal forecasts of CAOs.

One of the advantages of using indices that measure the strength of the meridional mass circulation is that they can be independently and explicitly calculated from the instantaneous total flow without the need for decomposition into time mean and transient flows nor the separation into zonal mean and wave flows. Therefore, one can calculate mass circulation indices directly from the output fields of operational models once they are generated without waiting for forecast outputs at other lead times (or initial conditions) for averaging, which is essential for issuing forecasts in real time. Another advantage is that the variability of the annular modes (e.g., NAM and AO) can be physically explained and numerically accounted for from the isentropic meridional circulation variation (Yu et al. 2014, 2015b), but not from the residual circulation because the latter does not have convergence–divergence by construction, although the isentropic meridional mass circulation is nearly equivalent to the residual circulation in the time mean sense (Pauluis et al. 2011). The association of the meridional mass circulation with baroclinic waves depends on the amplitude of the waves, their westward-tilting structure, and their spatial scales, rather than the exact locations of a trough and ridge. Therefore, an operational forecast model would have skillful forecasts for the intensity of the meridional mass circulation as long as it can capture the amplitude and the spatial structure even though it cannot accurately predict the locations of the troughs and ridges of these waves (Zhang et al. 2013), a conjecture to be further substantiated in the section on the skill evaluations of forecasts for the ST60N, CNA, and CEA indices during the 2013/14 winter. The circulation indices that are constructed from EOF modes of anomaly fields, such as the NAM index, may not be predictable by operational models in the subseasonal range because the models’ EOF modes are different from the observations in terms of both spatial patterns and explained variances (as well as their amplitude).

In this study, we consider indices that measure mass circulation intensity to illustrate the feasibility of subseasonal forecasts for CAOs in the midlatitudes in a real-time setting within the framework of the proposed hybrid paradigm. Since mass circulation intensity is directly related to temporal changes of mass fields (including the surface pressure tendency or the AO tendency), an anomalous intensification of mass circulation, which is referred to as a pulse, can be used as an indicator of a strong circulation event. We will use the total intensity of the stratospheric mass circulation predicted by operational models to detect the pulse and then use it in the statistical diagnostics model to forecast the occurrence probability of continental-scale CAOs in the midlatitudes.

DATA, METHODS, AND DEFINITIONS. The information from the datasets used in this study, including their resolutions and main usages as well as their acronyms, are summarized in Tables 1 and 2. All data are daily data at 0000 UTC. Below are details of the methods used to derive meridional mass circulation indices with various isentropic surfaces as the bottom level and the cold temperature area indices from these daily data.

Indices of meridional mass circulation. The time and zonal mean mass circulation in isentropic coordinates is characterized by a single thermally direct circulation cell in each hemisphere that links the heat source in the tropics to the heat sink in high latitudes (e.g., Johnson 1989; Juckes et al. 1994; Held and Schneider 1999; Koh and Plumb 2004; Schneider 2005, 2006; Pauluis et al. 2008). Pauluis et al. (2011) further proposed a statistical transformed Eulerian mean (STEM) formulation for an easy diagnosis of the time mean meridional mass circulation. We here diagnose the zonal mean meridional isentropic mass

<p>| Table 1. List of the datasets and their acronyms used in this study. |
|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full name</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFSR*</td>
<td>NCEP Climate Forecast System Reanalysis</td>
<td>Saha et al. (2010)</td>
</tr>
<tr>
<td>CFsv2</td>
<td>NCEP Climate Forecast System, version 2</td>
<td>Saha et al. (2014)</td>
</tr>
<tr>
<td>CFsRR*</td>
<td>CFsv2 Reforecasts</td>
<td>Saha et al. (2014)</td>
</tr>
<tr>
<td>NNR1b</td>
<td>NCEP–NCAR Reanalysis 1</td>
<td>Kalnay et al. (1996)</td>
</tr>
</tbody>
</table>

* Information online at http://nomads.ncdc.noaa.gov/data.php?name=access#cfsr.

b Information online at www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html.
circulation on a daily basis. Following Pauluis et al. (2008), we interpolated the daily air temperature and wind fields onto 200 equally spaced sigma ($\sigma$) levels from 1 to 0. The air mass $m_n$ between two adjacent sigma surfaces per unit area is $m_n = (\Delta \sigma / g) P_s$, where $P_s$ is the surface pressure in pascals, $g$ is the constant of gravity, and $\Delta \sigma = 1/200$. We then derived the zonally integrated meridional mass flux above a specific isentropic surface $\Theta$ at latitude $\phi$ on day $t$ as

$$F_m(\phi, \Theta_n, t) = \int_0^{\pi} \int_{\Theta_n}^{\pi} \left[ m_n(\lambda, \phi, t) v(\lambda, \phi, \sigma, t) \right] H[\theta(\lambda, \phi, \sigma, t) - \Theta_n] d\sigma d\lambda,$$

(1)

where $l$ is longitude; $v(\lambda, \phi, \sigma, t)$ and $\theta(\lambda, \phi, \sigma, t)$ are the meridional wind and potential temperature fields, respectively; and $H(x)$ is the Heaviside function, such that $H(x) = 1$ for $x > 0$ and otherwise $H(x) = 0$.

In this study, we only consider the meridional mass transport into the region north of 60°N [i.e., only $\phi = 60°N$ in (1) is considered]. We have considered several values of $\Theta_n$ as the bottom level of a layer above the tropopause at 60°N; namely, $\Theta_n = 330$, 350, 400, 450, 500, and 550 K. The results shown in the main text are obtained with $\Theta_n = 400$ K; namely, ST60N = $F_m(\phi = 60°N, \Theta_n = 400$ K, $t$), where ST stands for the stratospheric mass circulation. The results of other levels are shown and discussed in the online supplement to this paper.

**Indices of cold areas over midlatitudes of North America and Eurasia.** We now describe the method for indices measuring CAO activities over the midlatitudes (30°–60°N) of North America (120°–60°W) and Eurasia (0°–120°E). For a given dataset of daily surface air temperature (SAT) fields, we first calculate the climatological annual cycle (SAT) by averaging the daily SAT field at each grid point across all available years of the daily SAT dataset for each calendar day from 1 December to 28 February. The corresponding daily anomalies are obtained by subtracting SAT from the total SAT. The resultant daily surface air temperature anomaly fields are denoted as SAT'. The local standard deviation (LSD) of SAT' is derived from the long-time anomaly fields are denoted as SAT'. The local standard deviation (LSD) of SAT' is derived from the long-time

$$C_{\alpha} = \frac{\int_{\phi_S}^{\phi_N} \int_{\lambda_N}^{\lambda_S} H(-\alpha \times LSD - SAT') \cos \phi \cos \lambda \, d\phi \, d\lambda}{\int_{\phi_S}^{\phi_N} \int_{\lambda_N}^{\lambda_S} \cos \phi \cos \lambda \, d\phi \, d\lambda},$$

(2)

where $\int \cos \phi \cos \lambda \, d\phi \, d\lambda$ denotes an area integral over the domain specified in the integral, $\alpha$ is the mean radius of Earth, and $H(x)$ is the Heaviside function as in (1). We consider two cold temperature area indices for North America, denoted as CNA$_{\alpha}$ with $\alpha = 0$ or 0.5, whose domains cover a latitude span from $\phi_S = 30°N$ to $\phi_N = 60°N$ and a longitude span from $\lambda_N = 120°W$ to $\lambda_S = 60°W$. Similarly, we also consider two cold temperature area indices for Eurasia, denoted as CEA$_{\alpha}$ with $\alpha = 0.0$ or 0.5, whose domains cover a latitude span from $\phi_S = 30°N$ to $\phi_N = 60°N$ and a longitude span from $\lambda_N = 0°$ to $\lambda_S = 120°E$.

It follows that the CNA$_{0.0}$ (CNA$_{0.5}$) index is the percentage of area occupied by cold surface

**Table 2. A brief summary of the datasets and their main uses.**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Date range</th>
<th>Pressure</th>
<th>Surface</th>
<th>Vertical resolution</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFSR</td>
<td>1 Dec 2013–28 Feb 2014</td>
<td>$1° \times 1°$</td>
<td>T126</td>
<td>37 pressure levels from 1,000 to 1 hPa</td>
<td>Analysis of events during winter 2013/14</td>
</tr>
<tr>
<td>I Jan 1999–31 Dec 2009</td>
<td>$1° \times 1°$</td>
<td>Gaussian grids</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFSv2</td>
<td>1 Oct 2013–28 Feb 2014</td>
<td>$1° \times 1°$</td>
<td>T126 Gaussian grids</td>
<td>37 pressure levels from 1,000 to 1 hPa</td>
<td>Skill analysis of CFSv2 forecasts</td>
</tr>
<tr>
<td>I Jan 1999–31 Dec 2009</td>
<td>$1° \times 1°$</td>
<td>T126</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFSRR</td>
<td>1 Jan 1999–31 Dec 2009</td>
<td>$1° \times 1°$</td>
<td>T126 Gaussian grids</td>
<td>Surface air temperature field</td>
<td>Systematic bias corrections for CFSv2 forecasts of surface air temperature</td>
</tr>
<tr>
<td>NNRI</td>
<td>1 Jan 1948–28 Feb 2014</td>
<td>$2.5° \times 2.5°$</td>
<td>$2.5° \times 2.5°$</td>
<td>17 pressure levels from 1,000 to 10 hPa</td>
<td>Climatological information of mass circulation and CAOs</td>
</tr>
</tbody>
</table>

* We only use the daily surface air temperature fields of the CFSRR dataset for bias corrections of CFSv2 forecasts of surface air temperature.
air temperatures that are below the normal (below normal by at least 0.5LSD) over North America. The same thing can be said about CEA_0.0 and CEA_0.5, which are for Eurasia.

Definitions. Table 3 lists the percentile thresholds of ST60N, CNA_0.0, CNA_0.5, CEA_0.0, and CEA_0.5 derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis 1 (NNR1) during December–February (DJF) of 1948–2014. In this study, we refer to it as a strong event of mass transport across 60°N into the polar stratosphere or “a pulse of the stratosphere” (denoted as PULSE), when the ST60N index is above $6 \times 10^9$ kg s$^{-1}$ (70th percentile) for at least n consecutive days ($n = 2, 3, \ldots, 8$). Table 4 lists the total number of PULSEs, $M(n)$; their total number of days, $D(n)$; and the average peak intensity, $PI(n)$, as a function of $n$ during the period 1948–2014. It is seen that for $n = 2$, there are a total of 206 PULSEs in the 66 DJF or about 3 PULSEs per winter. This indicates that on average the hybrid paradigm would be able at most to forecast three rounds of CAOs based on the pulse information using this threshold value. Only one round of CAOs could be forecasted using the pulse information when the threshold for the duration is increased to 8 days. The fact that $PI(n)$ increases as $n$ increases implies that even if we use a constant intensity threshold for detecting PULSEs, we can use the duration days to indicate the intensity of a PULSE.

Individual CAOs are driven by mobile synoptic-scale weather systems. During a CAO event, cold-air temperature anomalies lie behind the troughs or in front of ridges, whereas warm temperature anomalies lie in front of troughs or behind ridges. Cold and warm temperature areas are relocated (eastward) as weather systems pass across a continent. Therefore, the condition that at least 50% area of a continent be occupied by cold temperature anomalies at any given day can be used to define a CAO event. Based on the discussion above, we refer to the condition that the daily value of a cold area index over a continent be above the $P$th percentile ($P = 50, 60, 70, 80, 90$) as a CAO event of intensity $P$ over the continent. Using the notations for the four cold area indices defined in (2), we denote CNA_0.0_P and CNA_0.5_P for CAOs of intensity $P$ over North America and CEA_0.0_P and CEA_0.5_P for CAOs of intensity $P$ over Eurasia. One can easily infer the total number of days of CAOs of intensity $P$ over a continent during the 66 DJF periods from the product of $(1 - P\%)$ and 5,940 (the total number of days in the 66 winter seasons).

<table>
<thead>
<tr>
<th>Percentile</th>
<th>ST60N ($10^9$ kg s$^{-1}$)</th>
<th>CNA_0.0 (%)</th>
<th>CNA_0.5 (%)</th>
<th>CEA_0.0 (%)</th>
<th>CEA_0.5 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>16.87</td>
<td>100</td>
<td>96.2</td>
<td>91.6</td>
<td>83.8</td>
</tr>
<tr>
<td>90th</td>
<td>8.28</td>
<td>77.4</td>
<td>60.5</td>
<td>70.7</td>
<td>51.2</td>
</tr>
<tr>
<td>80th</td>
<td>6.90</td>
<td>69.5</td>
<td>49.4</td>
<td>63.0</td>
<td>42.7</td>
</tr>
<tr>
<td>70th</td>
<td>5.96</td>
<td>62.8</td>
<td>41.0</td>
<td>56.8</td>
<td>37.3</td>
</tr>
<tr>
<td>60th</td>
<td>5.23</td>
<td>55.4</td>
<td>33.9</td>
<td>52.0</td>
<td>32.9</td>
</tr>
<tr>
<td>50th (median)</td>
<td>4.46</td>
<td>48.5</td>
<td>28.0</td>
<td>47.3</td>
<td>28.3</td>
</tr>
<tr>
<td>40th</td>
<td>3.96</td>
<td>41.7</td>
<td>22.4</td>
<td>42.9</td>
<td>24.4</td>
</tr>
<tr>
<td>30th</td>
<td>3.50</td>
<td>34.9</td>
<td>16.8</td>
<td>38.2</td>
<td>20.2</td>
</tr>
<tr>
<td>20th</td>
<td>2.90</td>
<td>28.0</td>
<td>11.4</td>
<td>32.9</td>
<td>15.8</td>
</tr>
<tr>
<td>10th</td>
<td>2.19</td>
<td>18.8</td>
<td>5.4</td>
<td>24.9</td>
<td>10.3</td>
</tr>
<tr>
<td>Min</td>
<td>−1.96</td>
<td>0</td>
<td>0</td>
<td>3.2</td>
<td>0</td>
</tr>
</tbody>
</table>

ASSOCIATION OF CAOS WITH THE STRENGTHENING OF MASS TRANSPORT INTO THE POLAR STRATOSPHERE. To illustrate the association of continental-scale CAOs with the strengthening of poleward mass transport into the polar stratosphere, we show in Fig. 2 the ST60N, CNA_0.0, CNA_0.5, CEA_0.0, and CEA_0.5 indices for the 2013/14 winter. It can be seen that there were three pronounced PULSEs (labeled as A, B, and D in Fig. 2a) with mass transport across 60°N into the polar stratosphere exceeding $6 \times 10^9$ kg s$^{-1}$ for a week consecutively. The first two PULSEs were back-to-back week-long strong circulation events that started on 31 December 2013 with a peak intensity of $9.2 \times 10^9$ kg s$^{-1}$ (above the 90th percentile). The PULSE D began on 31 January with a peak intensity of $11 \times 10^9$ kg s$^{-1}$ (about 95th percentile) and lasted 8 days. Sandwiched between the twin and the third...
PULSEs was a minor PULSE (labeled as C), a 2-day event during 19 and 20 January 2014, whose peak just slightly exceeded $6 \times 10^9$ kg s$^{-1}$ (70th percentile). Following the twin PULSEs A and B was a 14-day-long episode of CAOs in the midlatitudes of North America with 70%–80% of the area occupied by below-normal temperature anomalies or up to 60% of the area reporting below-normal temperature anomalies by at least half a standard deviation (both CNA_0.0 and CNA_0.5 exceeded the 90th percentile). A week-long massive CAO episode over North America with its cold area indices exceeding the 90th percentile followed PULSE D. Even the minor PULSE was followed by a 3-day-long weak CAO over North America. In the midlatitudes of Eurasia, however, there was only a 1-week-long episode of major CAO with the peak of CEA_0.0 or CEA_0.5 index reaching the 70th percentile level in the winter of 2013/14, which took place after the third pulse. It is important to point out that not all continental-scale CAOs are preceded by a stratospheric pulse, such as the major CAO that took place over the midlatitudes of North America during 9–21 December 2013. We have verified that during this period, there was little presence of large-amplitude planetary-scale waves in the stratosphere and, therefore, no strong circulation event in the stratosphere.

We next present statistical evidence supporting the idea that the relation between PULSEs and CAOs found in the 2013/14 winter holds for other years as well. To do this, we examine the occurrence probability of CAOs at different numbers of lead–lag days relative to the peak dates of PULSE events (Fig. 3) using the 66 yr of daily NNR1 data in DJF. For example, to construct the probability of the occurrence (PO) of CNA_0.0_P events, we count the total number of days of CNA_0.0_P events at $t_0$ days from the peak days of individual PULSEs, denoted as $N(t_0)$, with $t_0$ ranging from –10 to 25 days, where negative values of $t_0$ represent $t_0$ days before the peak days and positive values after. The PO of CNA_0.0_P at different lead–lag days relative to the peak dates of PULSEs is given by the ratio of $N(t_0)$ to the total number of PULSEs, $M(n)$, listed in the second row of Table 4, where $n$ is the duration threshold for PULSE events. In the same fashion, we obtain the PO of CNA_0.5_P, CEA_0.0_P, CEA_0.5_P, and CEA_0.5_P.

**Table 4.** Total number of PULSE events that last at least $n$ consecutive days, their total number of days, and their average peak intensity ($10^9$ kg s$^{-1}$) recorded during the 66 DJFs of 1948–2014.

<table>
<thead>
<tr>
<th>$n$</th>
<th>M(n)</th>
<th>D(n)</th>
<th>PI(n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>206</td>
<td>1,608</td>
<td>7.81</td>
</tr>
<tr>
<td>3</td>
<td>178</td>
<td>1,552</td>
<td>7.97</td>
</tr>
<tr>
<td>4</td>
<td>154</td>
<td>1,480</td>
<td>8.13</td>
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<tr>
<td>5</td>
<td>135</td>
<td>1,404</td>
<td>8.26</td>
</tr>
<tr>
<td>6</td>
<td>117</td>
<td>1,314</td>
<td>8.40</td>
</tr>
<tr>
<td>7</td>
<td>101</td>
<td>1,218</td>
<td>8.56</td>
</tr>
<tr>
<td>8</td>
<td>76</td>
<td>1,043</td>
<td>8.80</td>
</tr>
</tbody>
</table>

Fig. 2. Time series of various indices derived from the NOAA CFS Reanalysis (CFSR) for the period from 1 Dec 2013 to 28 Feb 2014. (a) The ST60N index ($10^9$ kg s$^{-1}$), (b) CNA_0.0 (purple) and CEA_0.0 (blue), and (c) the CNA_0.5 (purple) and CEA_0.5 (blue). The thin solid horizontal lines correspond to the median values of these indices (as shown in Table 2), while the dashed horizontal lines represent the 70th percentile thresholds of these indices. The shaded rectangular boxes in (a) mark the time spans of the four PULSE events—namely, the periods when ST60N exceeded the threshold of the 70th percentile—and those in (b) and (c) mark the time spans of CAO events defined by CNA 0.0_70, CEA 0.0_70, CNA 0.5_70, and CEA 0.5_70 (see text for details).
and CEA_0.5_P events at different numbers of lead–lag days relative to the peak dates of PULSEs.

To test the statistical significance of the PO of CAOs, we perform 5,000 Monte Carlo simulations using the same daily time series of CNA_0.0, CNA_0.5, CEA_0.0, and CEA_0.5. In each Monte Carlo simulation, we randomly select a set of \( K(N) \) dates \((N = 1–5,000)\) as the peak number of days of PULSEs in the 66-DJF period and evaluate the PO of CAOs at \( t_0 \) days from these randomly selected dates, with \( t_0 \) ranging from \(-10\) to 25. We then rank the PO of CAOs at \( t_0 \) days from the peak days of the observed PULSEs against the 5,000 samples of the PO at \( t_0 \) days from the randomly selected dates. A statistical significance at the 5% level for the above-normal PO is determined when the observed PO of the CAOs at a given lead–lag time exceeds the 95th percentile of the 5,000 simulated POs at the same lead–lag time. Similarly, a statistical significance at the 5% level for the below-normal PO is determined when the observed value falls below the 5th percentile of the 5,000 simulated PO values. We have done two sets of 5,000 Monte Carlo simulations for each cold area index: one with two adjacent randomly selected dates at least 8 days apart and the other without such a condition. The statistical tests from the resultant Monte Carlo simulations are nearly identical.

We have obtained the POs of CNA_0.0_P, CNA_0.5_P, CEA_0.0_P, and CEA_0.5_P events with \( P = 50, 60, 70, 80, \) and 90 as a function of the number of lead–lag days relative to the peak dates of PULSE events with different duration thresholds, \( n \). For the same value of \( P \), the PO of CNA_0.0_P (CEA_0.0_P) is nearly identical to that of CNA_0.5_P (CEA_0.5_P). Therefore, it suffices just to show CNA_0.5_P and CEA_0.5_P, as displayed in Fig. 3 for \( P = 50 \) (for cold area indices above the 50th percentile) and \( P = 70 \) (for cold area indices above the 70th percentile). It is seen that the PO needed for CAOs to occur over Eurasia is significantly above the climatological probability during 1 week before the peak day of a PULSE. The peak PO of CEA_0.5_50 (CEA_0.5_70) events can be as high as 68% (44%) on day 3 (4) before the PULSE’s peak day, which is a 36% (47%) gain from its climatology probability (equaling \( 1 - P \)). The PO for CAOs to occur over North America becomes significantly above the climatology probability in the second week after the PULSE’s peak day, with the peak probability of 63% (39%) on day 11 (16) for CNA_0.5_50 (CNA_0.5_70) events, a 26% (30%) gain from the climatological probability. The longer the duration (up to 8 days) of a PULSE is (which tends to be also a stronger PULSE), the higher the PO of the CAOs is. Comparison between the top and bottom panels of Fig. 3 indicates that the results are not sensitive to the threshold used for defining CAOs in terms of the timing information with respect to the peak days of PULSEs. However, the relative gain of the occurrence probability from the climatological probability is higher for more massive CAOs (detected by larger threshold \( P \) value). This implies that the skill

Fig. 3. Probability (solid color lines, %) of occurrence of (a) CNA 0.5_50, (b) CEA 0.5_50, (c) CNA 0.5_70, and (d) CEA 0.5_70 at different lead–lag times with respect to the peak dates of PULSEs with durations of \( n \) days or longer. Different colors correspond to different values of \( n \) (\( n = 2, 3, ... , 8 \)). The horizontal solid black line in each panel represents the climatological probability equaling the corresponding percentile threshold. The dots indicate statistical significance at the 5% level. Statistics are derived from the NNR1 dataset for the 66 DJFs of 1948–2014.
for relating CAOs to the peak days of PULSE is more robust for more massive CAOs.

We have constructed the PO of CAOs with respect to the peak days of PULSEs detected using different thresholds (the one for Fig. 3 is the 70th percentile threshold of the ST60N index). The timing information of the above-normal probability of CAOs is insensitive to the threshold value (as long as it is greater than the 60th percentile), as one may expect from the results of different duration time shown in Fig. 3 (recall that the duration time and intensity of a PULSE are positively correlated). We also have found that the larger the threshold intensity used to define a PULSE, the greater the above-normal probability for CAOs to occur, similar to the results of different duration times shown in Fig. 3. However, for a smaller threshold (say less than the 40th percentile), the diagnosed PO of CAOs approaches the climatological probability. Additional discussion of the threshold for detecting PULSE events is provided in the section offering a prototype hybrid paradigm for subseasonal forecasts of continental-scale CAOs.

**SKILL EVALUATIONS OF FORECASTS FOR THE ST60N, CNA, AND CEA INDICES DURING THE 2013/14 WINTER.** We now provide evidence suggesting that the CFSv2’s operational forecasts during the 2013/14 winter did possess useful skill in predicting the ST60N index more than 2 weeks in advance, whereas their skill in directly predicting CAOs degrades significantly beyond 2 weeks. It is seen from Fig. 4a that similar to the observations, the ST60N derived from the CFSv2 forecasts at lead times of 1–50 days showed a below-normal mass transport into the polar stratosphere for most of December, and significantly above-normal mass transport in January and early February. The CFSv2 forecasts not only reproduced the general pattern of the temporal evolution, but also captured the occurrence of individual PULSE events. The useful skill of CFSv2 in forecasting PULSEs at the subseasonal range can also be seen from the time series of the ST60N derived from forecasts starting at a given initial condition, which is along the direction parallel to the dashed lines in Fig. 4a. Nevertheless, the timing of the forecasted PULSEs was delayed by up to a week or so in the CFSv2 forecasts at a lead time of 2 weeks and longer.

Figure 5a shows the correlation skill of the operational CFSv2 forecasts for the ST60N index during the winter of 2013/14 as a function of forecast lead time and lagged verification time. We consider a correlation of 0.3 to be the cutoff for “marginally useful” skill in the subseasonal range, a term that is borrowed from the experience in predictions of upper-level (i.e., 500-hPa height) charts in the 6–10-day range (e.g., Zhang et al. 2013; Hamill et al. 2004). In the opening section of the online supplement, we provide detailed information on how the correlation skill at a given forecast lead time is evaluated at different lagged verification times. By design, the correlation skill at zero lagged verification time is exactly equal to the convectional correlation skill. It is seen that CFSv2 does possess useful skill (above 0.4) in predicting the ST60N index even when the lead time is longer than 2 weeks, particularly in the range between 35 and 45 days. Moreover, the correlation skill in the range between 15 and 35 days is substantially improved when we verify the forecasts at an earlier time (positive lag, which attempts to account for the delay errors of the CFSv2 forecasts). This confirms that the overall correlation skill of the operational CFSv2 forecasts for the ST60N index during the winter of 2013/14 remained above the 0.5 level throughout the 45 days of lead time after the timing error, which is within the range of 1–10 days, had been taken into consideration. Therefore, the operational CFSv2 forecasts indeed possess useful prediction skill for the isentropic meridional mass circulation above 400 K (also see Fig. ES10b in the online supplement) at lead times of 30 days and longer. However, the CFSv2 forecasts for the meridional mass circulation below 400 K (Figs. ES9, ES11, and ES10a in the online supplement) are no longer reliable beyond 2 weeks.

From a forecaster’s perspective, the “usefulness” or the actual skill that matters should be evaluated by following the lead-time series of the forecasted ST60N derived from the forecasts starting from the initial state when the forecast is made. In Fig. 4a, the real-time series of the forecasted ST60N is along the diagonal axis parallel to a dashed line, at which point the real time and forecast lead time are identical. It is seen that the twin PULSE events (PULSEs A and B) observed in the period of 1–15 January 2014 were detected by CFSv2 forecasts as early as 7 December 2013, which would provide forecasters useful information about the occurrence of PULSE events 20–40 days in advance. Similarly, the strongest PULSE event (PULSE D, 31 January–7 February 2014) observed in the 2013/14 winter was detected by CFSv2 forecasts as early as 26 December 2013, again within a lead time of 20–40 days. Moreover, these three major PULSE events showed up in most of the forecasts between the first detected data and their occurring dates except the obvious back-and-forth timing and duration errors of a few days. The combination of the back-and-forth timing errors and duration time errors make...
Fig. 4. Variations of various indices as a function of verification time (abscissa) during the 2013/14 winter and forecast lead time (ordinate): (a) ST60N ($10^6$ kg s$^{-1}$), (b) CNA$\_0.0$ (%), and (c) CEA$\_0.0$ (%). Day 0 in the lead time corresponds to the initial conditions of the CFSv2 forecasts. The white-shaded area corresponds to the climatological values derived from the NOAA CFSR for the period of 1999–2009. The dashed lines are along the diagonal axis at which the real time and forecast lead time are identical. The black-colored letters A–D mark the timing of the observed four PULSE events identified in Fig. 2, and those in red correspond to their counterparts detected from the five individual forecasts (i.e., the time series along the dashed lines).

The forecasted PULSEs appear “on” and “off” at the verification time, responsible for the relatively poor correlation skill at the verification time (i.e., the skill at lag 0 in Fig. 5a). It is important to point out that the PULSE C event, which was a 2-day PULSE event that just exceeded the threshold of PULSE events marginally, was not detected clearly until about 2 weeks before it happened. It appears that the difficulty in detecting the minor PULSE event from CFSv2 forecasts was mainly due to the large duration errors in forecasting the major PULSE B event that took place just a few days earlier. Therefore, CFSv2 can provide useful information for detecting large-amplitude PULSE events at a lead time of 20–40 days, except for timing and duration errors of a few days, but may not be able to do so for small-amplitude PULSE events. We will illustrate how to utilize the useful skill of the CFSv2 forecasts in detecting PULSEs 20–40 days in advance for real-time subseasonal forecasts of CAOs in the next section.

Turning our attention to the CFSv2 forecasts of CAOs, Fig. 4b shows that the CFSv2 forecasts were unable to capture the three massive CAOs over North
America beyond 2 weeks. This was also the case for the sole prolonged massive CAO over Eurasia in the first half of February (Fig. 4c). Figures 5b and 5c vividly show the week 2 cutoff limit of the CFSv2 prediction skill for the CNA and CEA indices. Beyond 2 weeks, there is a lack of continuity in the correlation skill of the CFSv2 forecasts of these indices even after we have taken the timing error into consideration.

A PROTOTYPE HYBRID PARADIGM FOR SUBSEASONAL FORECASTS OF CONTINENTAL-SCALE CAOS. Figure 6 outlines an operationally implementable procedure for a hybrid (dynamical plus statistical) paradigm for real-time subseasonal forecasts of continental-scale CAOs. Before starting the operational subseasonal forecasts of CAOs, one needs to build the statistical component that links the pulse of the stratosphere to the occurrence probability of continental-scale CAOs of different levels of severity (i.e., in terms of area coverage over a continent and intensity), as shown in Fig. 3. One can construct such a statistical model for the occurrence probability of CAOs as a function of the intensity and duration of PULSEs. In operational forecasts, one can derive the ST60N index as a function of forecast lead time using the operational model’s forecast outputs starting from the date when the forecasts for CAOs are to be made. PULSE events can be detected from the lead-time series of the forecasted ST60N index based on the forecaster’s choice. The forecaster can issue forecasts for the temporal distribution of the high probability for CAOs of different severity to occur by plugging the information related to peak days, duration time, and intensity into the preconstructed statistical model.

In this hybrid forecast paradigm, one needs to consider the balance between “missing forecasts” and “false alarm” forecasts in choosing the threshold for detecting PULSEs for the model’s forecast outputs. For a larger threshold, the PO of CAOs is higher and statistically more significantly above the climatology probability. However, one would have fewer CAO events to forecast because of the smaller number of PULSE events detected in the model’s forecast outputs. This may yield more missing forecasts of CAO. On the other hand, a smaller threshold would lead to more PULSEs detected from the model’s forecast. However, because 1) the model may not have useful skill in predicting small-amplitude PULSEs beyond 2 weeks and 2) the diagnostic information that links CAOs to PULSEs may not be statistically significant, a smaller threshold for PULSEs may lead to more false

**Fig. 5.** The correlation scores of the operational CFSv2 forecasts for DJF 2013/14 as a function of the forecast lead time (ordinate, days) and lagged verification time (abscissa, days): (a) ST60N, (b) CNA_00, and (c) CEA_0.0. The dotted area indicates statistical significance at the 5% level.
alarm detections of PULSE events from the model’s forecast output and more false alarm forecasts of CAOs even when the model could capture small-amplitude PULSEs accurately.

We next wish to use the results presented in Figs. 4a and 3 to demonstrate how such a hybrid paradigm could be used for forecasting CAOs during the winter of 2013/14 at a lead time longer than 2 weeks. Because the twin PULSE (A and B) events first detected on 7 December 2013 remained above the threshold continuously in the later forecasts, one could forecast on 10 December 2013 about the high probability for CAOs to occur over the period a few days before the new year through the first 10 days of 2014, which would be a (at least) 25-day forecast. Since its detection on 7 December, the forecasted PULSE event appeared to show up at a later time in later forecasts until around 26 December when the timing delay of its occurrence in forecasts stopped. Therefore, one could issue a forecast on 26 December 2013 to predict that a new round of CAOs would occur during the period between the last week of January and the end of the second week of February. This would make it a 30-day forecast.

The feasibility of the prototype hybrid paradigm for predicting continental-scale CAOs in real time 1 month in advance has been put to a test at Florida State University by a team consisting of three graduate students and three undergraduate students led by the first author. They issued experimental subseasonal forecasts in real time, which are accessible freely by the general public and archived online (www.amccao.com). As recorded at the website, they were very successful in forecasting CAOs and winter storms at a lead time of 3–6 weeks in advance for the 2014/15 winter season. Specifically, they issued forecasts for a total of 15 PULSE events of strong mass transport into the polar stratosphere during the period from 14 October 2014 to 30 April 2015 at an average lead time of 1 month since 29 September 2014. All of their forecasts have been confirmed to capture the peak times of these 15 PULSEs within the time periods of their forecasts. There were only three major peaks of strong mass transport into the polar stratosphere that were not forecasted (29 November 2014, 10 December 2014, and 23 January 2015). None of the forecasts issued resulted in a false alarm. Most importantly, all of these 15 strong stratospheric circulation events (or PULSEs) were accompanied by major CAOs over at least one of the two major continents. This is particularly the case for North America where an abrupt increase in the area of below-normal temperatures was recorded within a few days after each of the 15 PULSEs. The inaugural subseasonal forecasts for CAOs during the winter of 2014/15 will be summarized in a separate paper.

CONCLUDING REMARKS. We have discovered that CAOs over the two major continents in the Northern Hemisphere on average tend to take place within a short time period from 1 week before to 1 to 2 weeks after anomalously strong mass transport into the polar stratosphere (i.e., the pulse of the stratosphere or PULSE). We also showed that an operational model, such as the CFSv2, is capable of predicting the PULSE, namely, the timing of strong mass transport into the polar stratosphere at a lead time of 20–40 days. This enables us to utilize the statistical relation between PULSE events and CAOs to predict the timing of having an abnormally high probability of the occurrence of continental-scale CAOs 1 month in advance.

In the online supplement to this paper, we have demonstrated that the key well-known polar stratospheric circulation indices, such as the

![Image](https://example.org/image.png)

**Fig. 6.** Flowchart of the prototype hybrid paradigm for real-time subseasonal forecasts of continental-scale CAOs in the midlatitudes.
lower-stratospheric NAM index and polar stratospheric temperature anomalies, are dominated by low-frequency signals with long decorrelation time scales (about 3 weeks). From the mass circulation perspective, each PULSE event corresponds to a stronger poleward mass transport into the polar stratosphere, causing a rising in the polar stratospheric temperature and a decrease of the stratospheric NAM index. It often takes several consecutive PULSE events into the polar stratosphere to cause a substantial warming in the polar stratosphere and a substantial weakening of the polar stratospheric vortex. It follows that the low-frequency nature of the lower-stratospheric NAM index is a manifestation of the accumulative (or temporal integral) effect of multiple PULSE events. Furthermore, forecasts of PULSE events can be made all winter long, as we demonstrated in our experimental forecasts for the winter of 2014/15, since their success does not require the presence of stratospheric (major or minor) warming signals in the initial conditions, which is the case for the conventional strategy that relies solely on dynamical model forecasts (e.g., Sigmond et al. 2013; Tripathi et al. 2014).

We wish to add that only deep and large-amplitude baroclinic waves are capable of driving a stratospheric pulse that is connected to the troposphere. Therefore, the proposed hybrid prediction strategy may not be able to help predict continental CAOs associated with every anomalously strong tropospheric meridional circulation event nor cold events that are mainly created by underlying surface conditions (e.g., the “refrigerator” effect of snow cover).

It is noteworthy that the good skill found for the CFSv2 forecasts of PULSEs beyond the 2-week lead time for the 2013/14 winter was obtained without any systematic bias correction. The skill presented in Fig. 5a could be further improved after applying such bias corrections based on historical hindcasts made by the same model. Additionally, North American Multimodel Ensemble forecasts (Kirtman et al. 2014) may yield an even better level of skill for predicting PULSEs at a lead time longer than that obtained here, which is based on forecasts of a single model. Additionally, models with higher resolution may help to gain additional skill in predicting the stratospheric anomalies at a longer lead time (Marshall and Scaife 2010; Tripathi et al. 2014).

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REFERENCES


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AMS JOURNALS—BETTER THAN EVER!

It is interesting how quickly bad news travels, isn’t it? Conversely, good news seems to barely propagate at all if left to its own devices. Changing long-held impressions is even harder, and in some cases, even overwhelming evidence can barely make a dent. As an example, let me turn to the terrific news coming out of the AMS Publications Commission that seems to be taking a long time to filter effectively into the community.

The Publications Commission had its annual meeting in Boston a few months ago. For three days, the chief editors of all AMS journals, monographs, and BAMS, along with a few at-large members of the Commission and the AMS staff that work on the Society’s publications, met to discuss issues associated with scholarly publishing in general and AMS publications in particular. As always, it was a vibrant and engaging meeting, and as usual I was extraordinarily impressed by the continuing dedication and energy of the volunteers who make the AMS publications truly world-class.

The news at the meeting was universally positive, and record setting on nearly every front—from the number of manuscript submissions received, to the average time to first decision for those submissions, to the time to publication of accepted manuscripts. These records are just the latest data points mapping a trajectory of continued growth and improvement on all fronts that has been evident for the past several years. Through the efforts of many dedicated volunteers and professional staff, along with effective implementation of technological advances, the journals have grown, significantly increased the speed to publication, and maintained the very high quality that has always been a hallmark of AMS publications. The impact of AMS publications, which have always been ranked among the best in the world in our subject areas, also increased as measured by several objective metrics.

We are doing our best to let the author community know about the excellent performance of the AMS journals on all fronts so that they will not avoid publishing their work with AMS due to concerns based on incorrect impressions. As noted at the start of this piece, however, this can be a frustratingly slow process, and overriding long-held impressions is not easy (I still run into authors who complain about color charges even though those were eliminated three years ago).

Help us spread the good news. If it has been awhile since you have published in AMS journals, you will be pleased with the improved work flow and speed to publication that we currently provide. If you are considering doing so for the first time, know that along with the prestige and quality that have always been associated with AMS publications, we are able to offer a path to publication much faster than ever before.

Keith L. Seitter, CCM
Executive Director
Dennis L. Hartmann, a University of Washington (UW) professor of atmospheric sciences, is among 84 new members and 21 foreign associates elected as Fellows of the National Academy of Sciences. They were chosen in recognition of their distinguished and continuing achievements in original research.

Hartmann joined the UW faculty in 1977 after earning his bachelor’s degree in mechanical engineering from the University of Portland and his doctorate in geophysical fluid dynamics from Princeton University. His research looks at the atmosphere’s role in climate variability and change, and how the atmosphere interacts with the ocean in a changing climate. He has authored a climate science textbook and nearly 200 research papers, and is former chair of the UW Department of Atmospheric Sciences.

Hartmann has lectured since the early 1980s about the physics of greenhouse gases and climate change. In 2013, he was a coordinating lead author of the most recent international assessment of climate science, in which he helped review the evidence for global warming. Hartmann was previously elected as a Fellow of the American Association for the Advancement of Science, the American Geophysical Union, and AMS. His other honors include the NASA Distinguished Public Service Medal and the Carl-Gustaf Rossby Research Medal from AMS.

Joel N. Myers, founder, president, and chairman of AccuWeather, has been recognized by The Pennsylvania State University with the Distinguished Alumni Award, the highest recognition the university bestows on an individual. The prestigious award was presented at the Distinguished Alumni Awards ceremony in June during Penn State’s Alumni Reunion Weekend.

Myers received his B.S., M.S., and Ph.D. degrees in meteorology from The Pennsylvania State University, where he was an important influence as a faculty member for nearly 20 years and a force on the Board of Trustees for 33 years. He continues to serve as an Emeritus Trustee, demonstrating his lifelong commitment to education. He has awarded dozens of scholarships to Penn State students in meteorology.

10 QUESTIONS WITH . . .

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

David George
Meteorologist, KTUU, Anchorage, Alaska

What inspired you to go into broadcasting? Watching Harold Taft (KXAS-TV) as a second grader, and meeting Troy Dungan (WFAB-TV), who has continued as my mentor for 3.5 decades.

How has the field changed since you started? Models only allowed us an educated guess at tomorrow’s weather in the early 80s, but now we have predictability in the 10–14 day range that often verifies.

How do you want to be remembered? I would like to be remembered for my conversational delivery and accuracy in a half-dozen TV markets across various climate zones.

What is the best thing about what you do? The best thing is when I encourage people to protect themselves when dangerous weather is approaching and then to have them thank me later.
and information technology, and made the largest gift ever received by the Meteorology Department to fund the university’s state-of-the-art weather station, as well as donating one of the largest weather vanes in the world, which sits atop Beaver Stadium, and walk-in sundials at The Nittany Lion Inn and The Arboretum at Penn State.

Myers is a Fellow of AMS, and AccuWeather received the Corporate Award from the AMS for “nearly 50 years of exceptional innovation and leadership in weather applications and communication.” His other awards and recognitions include the National Weather Association Individual Achievement Award and election to the Pennsylvania Association of Broadcasters Hall of Fame. In 1992, Myers cofounded the American Weather and Climate Industry Association, and he continues to serve as a board member. He also serves on the board of The Committee for Economic Development. In addition, he has served five governors as one of the longest-serving members of Team Pennsylvania, and he has advised senators and U.S. presidential candidates on policy issues.

Sarah Long has joined Portland, Maine, ABC affiliate WMTW-TV 8 as a weekend meteorologist.

Previously, Long was the morning meteorologist at Portland CBS affiliate WGME for 10 years, and was previously the chief meteorologist at Mount Washington Observatory in New Hampshire.

A native of Merrimac, Massachusetts, Long is a 1997 graduate of the University of Massachusetts at Lowell and holds a B.S. degree in meteorology. She has earned both the AMS Broadcast Seal of Approval and CBM.

From 1995 to 2005, Long was an AMS DataStreme local implementation instructor, where each semester she trained weather education resource teachers. She also served on the AMS Board on Women and Minorities from 2001 to 2007.

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**What's been your most difficult moment on air?** A vicious on-air coughing episode from eating chips and tacos prior to a weathercast in 1985. I was still trying to speak about forecast details while gagging and turning purple.

**If you weren't a broadcaster, what do you think you would be?** I might be a middle-school science teacher or an overseas travel guide.

**What's one thing people would be surprised to learn about you?** I was only 20, and looked 16, when I started as a full-time meteorologist at KWTX-TV in Waco in August of 1983.

**What was the most important way to prepare yourself for this job?** Communication/broadcast classes help immensely, plus you must learn the pronunciation of all towns, cities, counties, lakes, mountains, and landmarks of the area where you work before you say any of them on television.

**What does being a “station scientist” mean to you?** To me, being a “station scientist” means speaking on behalf of the on-air team, in a professional and knowledgeable manner, about any topic that deals with geology, oceanography, astronomy, and meteorology.

**If you had an extra minute on the air, what would you talk about?** I would give thanks to my family for the endless sacrifices they’ve made because of my crazy work schedules, numerous public appearances, and the late-night or weekend severe-weather events that interrupted our plans.

*David George earned his CBM in 2010. For more information on AMS Certification Programs, go to [www.ametsoc.org](http://www.ametsoc.org).*
Over the last several years, the AMS has endeavored to strengthen its role in the international atmospheric, oceanic, and hydrologic community. These efforts have several objectives: to share the benefits of AMS membership, encourage participation in AMS meetings, and promote author- and readership of our journals abroad; to support the considerable number of AMS members, authors, reviewers, and editors who are located overseas; and to explore opportunities for collaboration with complementary organizations.

As a first step toward achieving these objectives, AMS has had an official presence (“the AMS booth”) at recent General Assemblies of the European Geosciences Union (EGU) and at Annual Meetings of the European Meteorological Society (EMS), has established a formal Memorandum of Understanding with EMS, and is exploring further ways to collaborate with these European counterparts. AMS also established bilateral agreements with the Canadian Meteorological and Oceanographic Society (CMOS), the Indian Meteorological Society (IMS), the Australian Meteorological and Oceanographic Society (AMOS), and the Chinese Meteorological Society (CMS). From the latter organization, two delegates recently visited the AMS Headquarters in Boston, Massachusetts, in recognition of this new partnership (see the post on AMS blog, The Front Page, for highlights about this momentous occasion at http://blog.ametsoc.org/columnists/distinguished-guests/).

At the AMS booth during the 2016 EGU General Assembly, Monique Kuglitsch, lead technical editor for the Journal of Hydrometeorology and AMS senior international outreach/communications specialist, sat down with three European scientists to learn about their career paths, their ongoing research, and the importance of international collaboration for furthering their field. The first interview featured Thomas Spengler, professor in the Geophysical Institute at the University of Bergen in Norway. Spengler has published in Monthly Weather Review, the Journal of Climate, the Journal of the Atmospheric Sciences, and BAMS. Since 2015, he has been the director of the Norwegian Research School on Changing Climates in the Coupled Earth System and the chair of the Atmospheric Working Group of the International Arctic Science Committee (IASC). The following text is adapted from the interview (watch the complete interview on the AMS YouTube page at www.youtube.com/watch?v=7YeC-oB2CE), and watch for excerpts of the other two interviews in future issues of BAMS.

Kuglitsch: You are originally from Munich, Germany, which is in the alpine foreland. Some of your research has looked at the behavior of atmospheric flow over mountainous topography. Did growing up near the Alps, a region with very unique atmospheric behaviors, motivate you to study atmospheric sciences? Spengler: That certainly contributed to that [. . .] I was always keen on hiking in the mountains, and when I was studying I developed an interest in paragliding and this was really meteorology live, being in the atmosphere [and] experiencing what you learn in the lecture hall. The project that you mentioned was actually motivated through paragliding. There was a special wind phenomenon in the area where I learned to paraglide and no one understood it. So we went out and did an experiment, which I led, and that was a huge inspiration, being able to do that. And, we understood the phenomenon in the end.

Kuglitsch: Your research has explored extratropical cyclones, polar lows, and atmosphere–ocean–ice interactions, and often combines theory, observational data, and modeling. How does each of these types of information contribute to a better understanding of atmospheric phenomena? Spengler: I’m really into the theoretical side. Of course, it’s very difficult to put everything into a theoretical context because the system is so complex. This is where models are really handy. With a model, you can put all of the physics in there, you can manipulate the system to a certain extent so that you understand the interactions, and you can play with your theory or your model. But, it needs a reality check. So, this is why you have to go out there and actually validate if your hypotheses, ideas, theories, and modeling experiments make any sense. This is why I think that everyone should combine these three elements in his/her research because that’s the only way that you can stitch things together.

Kuglitsch: To gather observational data, your field work has brought you beyond the mountains—you have spent time on research vessels in the Arctic and at the Gulf of Carpentaria, Australia. Can you
tell us about the challenges of field work in these environments?

Spengler: They couldn’t be more different, right? One was at ~15°S, so in the tropics—the Gulf of Carpentaria is in northern Australia—and the other was on a German icebreaker north of Svalbard, it at was ~82°N, in the ice. So, both locations were isolated in a way.

We lived in a little village in northern Queensland in Australia for the experiment and there was a beautiful beach but you weren’t allowed towards the beach because there were these crocodiles. So, these were the kinds of things you needed to deal with.

On the icebreaker, it was a different challenge, because you were together and you couldn’t escape. You had to very closely work together and there will be friction, of course, but you had to learn to deal with it, and it comes down to very good leadership. To me, on the ship, it was [also] very inspiring because, unlike the field campaign—where it was just us, atmospheric scientists, 15 of us—on a research vessel, especially a big one like Polarstern, the one that I was on, there were 50 researchers, which means that they were from different disciplines. That way, you learned something about biology, about geology […] and you learned how to connect and how it all goes together. And, I love the arctic, I have to say.

Kuglitsch: Following your education, you spent time working at NOAA’s Geophysical Fluid Dynamics Laboratory at Princeton University. Since 2010, you have been a faculty member at the University of Bergen, Norway. How did your education and prior work experience prepare you for your professorship?

Spengler: I really encourage early-career scientists who want to make a career in academia that teaching will be part of your career so take some courses; otherwise it will be a very cold shower once you hop in there. I also learned a lot by communicating with my supervisors, before I took on the professorship, and something that I very much appreciated at Princeton University was that they offered a fantastic program for graduate students, and a course that I very thoroughly enjoyed was called PROF101. I think that these kinds of courses help early-career scientists to ease into academic careers.

AMS STATEMENT

WEATHER, WATER, AND CLIMATE PRIORITIES

A Policy Statement of the American Meteorological Society

(Adopted by the AMS Council on 26 May 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.

INTRODUCTION. 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. 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 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.

RECOMMENDATIONS. Economic and social prosperity belong to a society that understands and effectively responds to Earth’s changing WWC conditions. To meet this challenge, the following actions are required:

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 geo-sciences, 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 best interests of the nation, effective leadership and management approaches will be needed, including (i) appointing strong, qualified, and diverse leaders to top WWC policy positions in the White House and Federal agencies, and (ii) implementing management structures that support integrated WWC research and services planning and budgeting across Federal agencies and the Congress. These structures should proactively engage the academic and private sectors.

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1 www.esa.doc.gov/economic-briefings/value-government-weather-and-climate-data
EXPECTED OUTCOMES AND CONCLUSION. Implementing these recommendations will better enable individuals, communities, businesses, and governments to manage risks and explore opportunities associated with changing WWC conditions. Economic and social prosperity will be enhanced, and further progress will be made toward saving lives, enhancing commerce, protecting property, and adapting to a changing world. In so doing, our nation will advance its leadership in promoting technological innovations that are critical to the success and well-being of a global society.

[This statement is considered in force until May 2021 unless superseded by a new statement issued by the AMS Council before this date.]

OBITUARIES

WILLIAM M. GRAY
1929–2016

William Mason (Bill) Gray passed away peacefully surrounded by his family on April 16, 2016 at the age of 86. He had been on the faculty at Colorado State University specializing in tropical meteorology from 1961 through his formal retirement in 2005. Following his retirement, he remained active in both hurricane and climate change research up until the time of his death. He was best known among the general public for his seasonal Atlantic basin hurricane forecasts but also contributed many fundamental studies in tropical cyclone structure, intensity, and climatology as well as cumulus convection, radiation, and the energetics of the tropics. Among the research community, he was legendary as a professor with more than 70 masters and Ph.D. students, many of whom went on to become leaders in the field of tropical meteorology. He was also a forceful presence at major scientific meetings, forever challenging the existing paradigms or current understanding of the field.

Internationally, he united the field of tropical cyclone researchers and forecasters around the world. He spent several months in 1978 on a World Meteorological Organization (WMO)-sponsored trip touring 28 global tropical cyclone warning centers. His report following that trip thoroughly detailed the observational challenges facing these centers. He initiated and organized the first WMO International Workshop on Tropical Cyclones (IWTC) in Bangkok in 1985. The IWTC continues to be held every four years and is a critical forum where forecasters and researchers can get together and discuss areas of progress and fundamental challenges that still need to be solved. Subsequently, in the era of e-mail availability, his research project set up an international tropical storms e-mail discussion list, open to professionals in the field from anywhere around the globe. Through the IWTC and the tropical storms e-mail discussion list, hurricane forecasters and researchers feel they are part of a global community, thanks largely to the initiatives and foresight of Gray.

Gray was born in Detroit, Michigan, on October 9, 1929. He was the eldest son of Ulysses S. and Beatrice Mason Gray. In 1939, the family moved to Washington, D.C., where Bill grew up in the northwest section of the district. He graduated from Wilson High School and George Washington University (1952), and was very active in high school football and baseball. A knee injury at age 21 prevented a desired career in professional baseball.

Gray received a second lieutenant commission in the U.S. Air Force in 1953 and served as a weather forecast officer for four years, the majority of which was overseas in the Azores and then in England. After joining Colorado State University, he remained active in the Air Force Reserves as a weather officer until 1974, when he retired as a lieutenant colonel. After his active U.S. Air Force duty in 1957, he obtained an M.S. (meteorology, 1959) and then a Ph.D. (geophysical sciences, 1964) from the University of Chicago under the tutelage of Herbert Riehl, often referred to as “the father of tropical meteorology.” He joined the newly formed Department of Atmospheric Science at Colorado State University in 1961.

Bill married Nancy Price from Oshkosh, Wisconsin, on October 1, 1954. They had four children,
Sarah, Anne (deceased), Janet, and Robert. Nancy Gray was very active for many years in Fort Collins community affairs and politics—including serving as mayor of Fort Collins in 1980–81—before her death in 2001.

Bill’s early research work at Colorado State University in the 1960s consisted of fundamental research into hurricane structure. His seminal research paper in 1968 titled “Global View of the Origin of Tropical Disturbances and Storms” published in *Monthly Weather Review* was the first paper to thoroughly document a global climatology of tropical cyclone frequency with physical mechanisms forcing the global variations and annual cycle, the contents of which are still the basis of many studies on tropical cyclones. One of his fundamental contributions was an elucidation of six necessary parameters for tropical cyclone genesis. These six genesis parameters are still utilized extensively by the hurricane research and forecasting community today. He and his students also spent considerable time painstakingly analyzing hurricane aircraft reconnaissance data that helped improve the understanding of the inner and outer circulations of the hurricane. Throughout his career, he and his students published extensively on various aspects of tropical cyclone genesis, structure, intensity change, climatology, and motion.

In addition to his work on tropical cyclones, Gray spent considerable amounts of time studying tropical convection and its associated impacts on radiation. His papers documenting how the heat release in tropical convection is transferred to the larger-scale circulation are fundamental to the cumulus parameterization schemes that are utilized by climate models today. He also provided better understanding of the diurnal cycle of deep convection, convincingly demonstrating that tropical convection has a maximum in the early morning and a minimum in the late afternoon—a concept that has been proven recently using satellite observations.

Beginning in 1984 and continuing to his death, Gray authored seasonal Atlantic basin hurricane forecasts. Prior to 1984, there were no predictions of Atlantic seasonal hurricane activity. These forecasts arose from the discovery that El Niño decreased Atlantic hurricane activity through increases in vertical wind shear, along with several other factors. He continued to refine the statistical models and incorporate new data sources as they came online through the 1980s and the 1990s. This initiative has prompted many others to follow suit, which has led to a number of seasonal tropical cyclone forecasts for different ocean basins. Even after stepping down as first author on the forecasts following the 2005 hurricane season, he continued to provide guidance with all predictions, including the April 2016 forecast that was released only two days before his death.

Gray had strong disagreement with the science behind the human-induced global warming hypothesis, and devoted the major portion of the last decade to researching this area. His primary argument was that the increased global temperature associated with CO₂-induced warming would lead to an increased hydrologic cycle. The faster hydrologic cycle would decrease surface temperature through the evaporation term in the surface energy balance while simultaneously increasing tropospheric temperatures. The faster hydrologic cycle would also result in enhanced cumulus convection with increased surrounding-area subsidence. Overall, he argued that this would lead to a decrease in upper-level tropical relative humidity, resulting in a negative water vapor feedback mechanism that would counteract significant levels of global warming.

Gray was famous as a professor. His enthusiasm and passion for research and data were boundless, and he always encouraged his students to be curious and to solve big problems. He always had a large research project team, including many international students who came to the United States specifically to work with one of the world’s leading researchers on tropical cyclones. There were group meetings held every week, long discussions and arguments through the afternoon into the early evening, and regular social events at his house in downtown Fort Collins. When the students accompanied him to science conferences, they were always introduced to the leaders in the field, and the work of his students was widely advertised. The research seemed to go on, as a team, nonstop, 24 hours, seven days a week, and for the students, it seemed they were at the center of the research universe.

His presence at the biannual AMS conference on hurricanes and tropical meteorology was a feature of these meetings. His presentation was always to a packed room, and he became famous for various expressions. In studies of the general circulation and of tropical convection, he always extolled the importance of vertical mixing by cumulonimbus convec-
tion, and became known for his catch-phrase “up moist-down dry,” referring to the upward motion in a convective core following a moist adiabat, and the large-scale downward motion in the Hadley Cell and trade wind regions following the dry adiabat. There was also the famous expression known as “the Bill Gray question,” where after a theoretical or dry presentation, he would congratulate the author on his insights, enthusiasm, and hard work, but would ask, “But what does it all mean?”

Gray received many awards during his distinguished career, including being named a Fellow of AMS. He won AMS’s Jule G. Charney Award in 1993 and was a corecipient of the AMS’s Banner Miller Award that same year. The National Hurricane Conference gave him the Neil Frank Award in 1995. He was ABC television’s “Person of the Week” in September of 1995. The National Tropical Weather Conference gave him the Bob and Joanne Simpson Award in 2014.

He also worked extensively with AMS during his career. He was a panel member of the AMS’s Committee on Hurricanes and Tropical Meteorology from 1968 to 1973 and 1978 to 1981. He later served as the chair of that committee from 1987 to 1990.

Gray’s imprint on the field of tropical meteorology is enormous, as evidenced by the very large number of meteorologists under his lineage in the tropical meteorology family tree produced by Bob Hart at Florida State University.

In most fields of science, the aged professors are treated with deference and reverence due to their past contributions. Unfortunately, Gray missed that period. Following his scientific instincts, he rejected much of the modern science of climate change and became a prominent climate change skeptic. The gentlemanly manners and generosity of spirit for which he was famous occasionally deserted him, and he sometimes engaged other scientists in personal attacks. His former students and colleagues rallied around him, and many colleagues went to great efforts to temper this behavior.

After Gray’s death, the tropical storms e-mail discussion list that his research project first developed lit up with personal reminiscences from scientists around the world. Lance Bosart of SUNY-Albany wrote about the climate skeptic: “We all know that Bill became a skeptic about the significance of human activity with regard to climate change. While I believe that Bill was on the wrong side of this debate, there is no question that he was very passionate about what he believed was insufficient hard evidence to justify the widespread conclusion that human activity was the cause of ongoing climate change. I am also aware that hurt feelings arose between Bill and some of his colleagues and former students over this issue. I fervently hope that with the passage of time these hurt feelings will recede. After all, in the ‘ledger of life’ there is no one alive or dead who doesn’t have at least a few marks on the negative side of his/her own personal ledger. We have lost a giant in the field who will leave a lasting legacy in the science of hurricanes, tropical meteorology, and operational hurricane forecasting. We need to remember, treasure, and celebrate Bill’s many outstanding intellectual, educational, and personal achievements.”

Gray kept working, and kept publishing to the end. His publication career spanned 54 years. It began with a paper in the *Quarterly Journal of the Royal Meteorological Society* in 1962 on the radial balance of forces in hurricanes, and ended with a paper that he cowrote with a team including his final Ph.D. student, Phil Klotzbach, in *Nature Geoscience* in 2015, the year before he died, discussing the potential end of the active Atlantic hurricane era.

William Gray was a scientist through and through. He lived, breathed, ate, and drank science. He always told his colleagues he wanted to die “with his boots on.” A few days before he died, he was released from the hospital to be at home under hospice care. During those last few days, he corresponded by e-mail with all his former students via his administrative assistant, who read the response e-mails to him. He had pages of yellow legal pad with equations and graphs scattered around his bedroom, as he continued working on a paper that he was preparing for publication. In his view, he died “with his boots on.”

Gray is survived by his two daughters, Sarah (of San Diego) and Janet (of Fort Collins), and his son, Robert, and two grandsons, Mason and Liam (of San Diego).

—Phil Klotzbach, John McBride, Chris Landsea, Johnny Chan, William Frank, Pat Fitzpatrick, and Lance Bosart
Allen H. Weber, who helped found the meteorology programs at the University of Oklahoma and North Carolina State University, passed away unexpectedly in Augusta, Georgia, on July 20, 2015. Allen was born on May 15, 1938 in Lorenzo, Idaho, the son of Alexander and Florence Weber. Allen received a B.S. in physics from Brigham Young University in 1960, a master’s in physics from the University of Arizona in 1962, and a Ph.D. in meteorology (with an emphasis on atmospheric turbulence and diffusion) from the University of Utah in 1966 under the direction of Shih-Kung Kao, a well-known atmospheric turbulence expert. He met and married his wife of 56 years, Jilene, in 1959, and they had three children, Michael, Dale, and Alene. Allen and Jilene also had five grandchildren.

Allen began his professional career at the University of Oklahoma in 1966, where he worked with Walter Saucier and Yoshi Sasaki to build the newly formed Department of Meteorology. He taught primarily dynamics and boundary layer meteorology courses to graduate and U.S. Air Force students. In 1969, he assisted Saucier in establishing a new meteorology program at North Carolina State University (NCSU). After teaching graduate and undergraduate courses and developing the academic program at NCSU for eight years, Allen left in 1977 to work at the Department of Energy’s (DOE) Savannah River Laboratory (SRL, the predecessor to the Savannah River National Laboratory, SRNL), as part of the Savannah River Plant (later called the Savannah River Site).

At SRNL, Allen performed wide-ranging research on mesoscale atmospheric transport and dispersion, atmospheric boundary layer turbulence, a wind climatology of the South Atlantic Bight, dense gas dispersion, effluent stack design, and emission of effluents into the atmosphere. In the early 1980s, Allen organized a dispersion modeling workshop at Kiawah Island, South Carolina, and participants included members of several national labs, the National Oceanic and Atmospheric Administration, the Nuclear Regulatory Commission, and the Environmental Protection Agency. Allen was then the principal investigator of two intensive field experiments in which perfluorocarbons were released via SRS facility stacks. This work was funded by the DOE Office of Health and Environmental Research. The first of these was the Mesoscale Atmospheric Transport Study, performed over many days during 1983–86 in generally unstable daytime conditions, while the second campaign was the Stable Atmospheric Boundary Layer Experiment (STABLE), performed on several nights in the spring of 1988. Both Allen and Jilene served as key statisticians and experts in the subsequent mesoscale model validation study undertaken by SRL. It should be noted that Allen was one of the earlier Certified Consulting Meteorologists, obtaining number 133 awarded in 1974. He retired from full-time employment at SRNL in 2005, but remained active as a consultant for the remainder of his life, continuing to provide guidance in atmospheric boundary layer work and statistical analysis of very large datasets. The final publication of his career on wind gust distribution analysis related to solar farm heliostat design was published shortly after his death.

Allen was also very dedicated to the local Palmetto Chapter of AMS, serving as president several times over the span of almost 30 years, and founding an annual minitechnical conference in the region performing research and applied developments in the atmospheric sciences. Participants from all parts of South Carolina, as well as Georgia and North Carolina, gather together on an annual basis to share the results of their latest work. At the 22nd meeting in spring 2016, held in Columbia, South Carolina, the conference was renamed in Allen’s honor.

In addition to his steady influence at work, Allen also had many passions that kept him busy. In addition to his family, Allen was also an avid music and arts enthusiast, supporting the local opera and symphony, as well as regularly attending theatrical productions. He even played in a bluegrass band for a period of time. He also enjoyed exercising, regularly participating in area running events, as well as triathlons. This served him well during his professional career, when in the 1970s he scaled a 300-meter tower to inspect and repair meteorological equipment as part of an experiment. His passion for enjoying lake winds was evident in his membership for many years in the Augusta Sailing Club. After his semiretirement in 2005, Allen and Jilene were fortunate enough to take a number of trips to many parts of the world, including Europe, Russia, and China. Allen was a valued mentor and friend to many in the meteorological community, and he will be sorely missed.

—Robert L. Buckley, Robert J. Kurzeja, Matthew J. Parker, and Darrell W. Pepper
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It’s once again election season at AMS. The 2016 candidates for AMS President-elect are Christa Peters-Lidard and Roger Wakimoto. This year’s candidates for AMS Councilor are: Private sector—Elizabeth Austin, Peter Neiley, Sheldon Drbot; Government—John Cortinas, Gary Geernaert, Tanja Fransen; Academic—Jeff Collett, John Nielson-Gammon, Adam Sobel.

When voting for councilors, members should choose one candidate from each sector group and an additional candidate from any group. The candidate with the highest vote count in each sector group will be elected, along with the candidate with the most votes after those three.

To help the membership select its leaders, the Society asked the candidates to answer the following question, “What do you see as the challenges facing the Society, and how would you address them if elected?” Following are their responses, along with a brief biographical sketch of each candidate.

AMS PRESIDENTIAL CANDIDATES

CHRISTA D. PETERS-LIDARD

As we approach the 100th anniversary of the AMS—the leading scientific and professional organization for atmospheric, oceanic, and hydrologic sciences—the increasing demand for accurate and timely weather, water, and climate information represents a tremendous opportunity for the Society. The AMS has long been recognized as a positive force for promoting unbiased scientific communication in the atmospheric and related sciences through its journals, meetings, statements, and policy briefings. However, as the public increasingly demands clear, transparent, quantitative, and continuous environmental assessments that go well beyond traditional disciplinary boundaries, the Society must be poised to marshal and channel the significant diversity of resources and experience in the Society to maximize the use and impact of our collective expertise for the benefit of all.

As president, I would work with members and leadership to ensure that AMS addresses the following issues to transform this vision into a reality:

• Engage and retain basic researchers in the atmospheric and related sciences through stimulating, open, and nimble scientific conferences and symposia and high-quality publications.
• Embrace the private sector and its contributions to innovation in the evolution of the weather and climate enterprise.
• Encourage and support the public sector as it continuously improves the nation’s environmental observing and prediction capabilities for the benefit of society.
• Enable effective communications reflecting the state of science and technology with policymakers and the public.
In an era of shrinking budgets, the AMS can serve as a beacon of multidisciplinary research, education, and communication, built on the foundation of the diverse intellectual and organizational resources of the membership from the academic, public, and private sectors. Observing, modeling, understanding, and predicting the Earth system have never been so crucial and yet so constrained by political, economic, and disciplinary "stovepipe" pressures. To help raise awareness and promote productive discourse, innovative, coordinated, and simultaneous cross-platform (e.g., symposia, journals, social media, and policy briefings) communications on key multidisciplinary topics could channel Society resources. Similarly, joint conferences with other disciplinary scientific societies to emphasize cross-discipline linkages could be pursued. Finally, scholarships, graduate research fellowships, and curriculum statements that promote multidisciplinary education could be essential for training the next generation of Earth science, applications, and policy professionals.

I am honored to be a candidate for AMS President, and if elected, I will apply my enthusiasm and experience on STAC, Council, EC, and as a chief editor to enable AMS to thrive as the premier scientific and professional society for atmospheric and related sciences. Thank you for your consideration.
at headquarters and through its Council, being strategic and visionary while soliciting constructive feedback from the community.

Other challenges facing the AMS with possible paths forward include

- continuing to emphasize the recruitment of underrepresented minorities by increasing outreach, emphasizing community-based research, and working with other professional and scientific organizations;
- increasing AMS membership by reaching out to students, early-career professionals, and the international community in order to communicate the importance and relevance of the Society;
- increasing the scientific profile of the Annual Meeting by highlighting important discoveries/breakthroughs within the STAC disciplines and ensuring that the appropriate topical sessions are offered that allow scientists to discuss and debate the most important research questions and hypotheses that our community faces;
- examining the various outreach mechanisms such as social media, e-mails, and the web pages in order to optimize their effectiveness.

It is truly an honor to be a candidate for AMS President. Much of what I have achieved to date has been through my involvement with the AMS, including publishing in their journals and attending a wide variety of their meetings and workshops. I can commit to being a tireless advocate for the AMS, listen and be responsive to the needs of all sectors of the Society to the greatest extent possible, and be forward-looking to prepare the AMS for the future challenges and opportunities that lie ahead.
The atmospheric and related sciences are in the midst of a very exciting time. Our sciences’ popularity is growing by leaps and bounds in terms of the media coverage it receives. However, this brings with it the responsibility of the AMS and its members to continue to respond to the needs for expertise and accurate analysis of current events. In addition, societal needs are changing in the way the majority of the population receives their data and information, and the AMS must continue to grow and expand its ability for reaching out to society in regards to its providing timely information and responses.

Another challenging area where the AMS must continue to expand its arena is in private sector/government/academic partnerships. As the founder and president of a small, private weather company, I know that this is an arena that is critical to the continued growth and success of the AMS and our members. There must be not only more emphasis on connecting the larger weather/oceanic/hydrologic/environmental companies with the government and academic sectors, but also a focus on the small companies that make up the majority of the businesses in our field. This can be done through AMS sponsorship of more short courses and events catered to smaller companies with help from such groups as the AMS Certified Consulting Meteorologists and Certified Broadcast Meteorologists, and the National Council of Industrial Meteorologists. In fact, the Certified Broadcast Meteorologists are a natural conduit between the AMS and the media.

Lastly, the AMS represents the atmospheric, space, hydrologic, oceanic, and many other related sciences. With the Earth–atmosphere system as a guide, the AMS must ensure that all of our respective sciences work closely together at events, conferences, and—most importantly—in our collaborative research. I believe that our scientific community will benefit greatly by putting more emphasis on things such as joint conferences and creating pathways for more collaborations among our sciences.

It will be an honor if I am elected Councilor of the AMS. If elected, I will work closely with the other members of the Council, the Executive Committee, and the membership to ensure that we address these important issues and develop lines of communication of to help take the AMS into the next era of scientific discoveries.
One of the strengths of AMS is its representation from academic, industry, and government sectors. It can, however, be a real challenge to meet the needs of such a diverse constituent group while maintaining the benefit of strong interaction across all sectors. AMS is deep into discussions on this topic and I look forward to working with Council to act upon recommendations from the membership and AMS committees on this matter. The Annual Meeting is one place where this discussion is highly relevant. For many current and potential members from the research community, the proximity of the Annual Meeting to the AGU Fall Meeting is problematic, forcing members to choose one meeting and/or organization over the other. This conflict needs to be resolved so that AMS can grow and more broadly attract members from a wide range of atmospheric science subdisciplines while maintaining meeting access for undergraduate students and other member constituencies who like the current timing of the Annual Meeting.

I also am anxious to promote cross-disciplinary meetings within AMS. As chair of last year’s AMS Atmospheric Chemistry Conference, I witnessed the excitement and energy in sessions coorganized by multiple AMS committees. Our ability to understand how the atmosphere works, how to better forecast its future behavior, and how to communicate impacts of atmospheric phenomena requires that we sometimes step beyond our many individual disciplinary meetings to interact with each other.

I am also very interested in promoting education in our field. I am amazed every year to talk with dozens of undergraduates who are fully energized by their participation in the AMS Annual Meeting. This is a component sometimes missing from meetings of other professional and scientific societies, and something we need to sustain and enhance. As someone who came to atmospheric science from outside of meteorology, I also want to help AMS better reach others from outside our traditional disciplinary boundaries. There is a lot of talent out there, and we should do our best to interest these folks in working on the exciting challenges within atmospheric science. By the same token, we need to do a better job recruiting a more diverse pool of scientists and professionals to our field. This is an area where we have had significant success in our graduate program at Colorado State University; I look forward to working with AMS to help stimulate similar progress more broadly in our field.
The AMS is clearly the nation’s preeminent professional organization serving the atmospheric sciences community and the general public, providing resources to help strengthen the weather, water, and climate sciences. It is my desire to ensure our world-class organization can serve the nation for decades to come. To maintain its premier status in the future, I see several challenges that I would like to help the AMS address.

The continued strength of the weather, climate, and water enterprise depends on ensuring there will always be talented individuals to participate in the future workforce. I believe I can help the AMS address this issue by developing policies of inclusion to ensure the participation of a diverse group of people in all its activities, including a diversity of experience, disciplines, age, gender, ethnic and racial backgrounds, sexual orientation, and other experiences that will benefit the AMS mission.

The AMS is an important non-partisan, trusted scientific organization, functioning as an honest information broker for the nation, and it must remain this way to be effective. This role is critically important in a society that finds itself constantly engaged in political wrangling on important societal issues. I will help to maintain this important role for the AMS within the enterprise and support fact-based scientific discourse in all of the Society’s policy programs, and help find ways for the AMS to continue educating the nation on these important topics.

Like many other organizations, the AMS will constantly be challenged to keep up with technological advances that would serve its members well, particularly in an increasingly mobile society. This is especially important for members of the organization who have limited travel opportunities. I will work with the AMS to continue looking for more opportunities to allow people to participate remotely and collaboratively in AMS conferences and other activities.

**JOHN CORTINAS (GOVERNMENT SECTOR)**

John CortinaS is the director of the Office of Oceanic and Atmospheric Research’s (OAR) Office of Weather and Air Quality (OWAQ) at the National Oceanic and Atmospheric Administration (NOAA), managing an $18M weather research budget on behalf of the American taxpayer. As the director of OWAQ, he also oversees NOAA’s U.S. Weather Research Program, hosts the National Earth System Prediction Capability program office, and is the portfolio steward for OAR’s weather research portfolio. Prior to joining OWAQ, he was director of OAR’s Cooperative Institute program, where he oversaw grant management activities and policy development for NOAA’s cooperative institutes across the United States, which conduct research at academic institutions in all areas relevant to NOAA’s mission.

Cortinas received a bachelor’s degree (1987) in meteorology from Metropolitan State College of Denver and a Ph.D. (1992) in geophysical sciences from the Georgia Institute of Technology. He worked as a postdoctoral fellow, a research scientist, and ultimately as the assistant director for NOAA relations at the Cooperative Institute for Mesoscale Meteorological Studies at the University of Oklahoma from 1992 to 2003.

His research specialties include hazardous winter weather, severe storms, mesoscale atmospheric phenomena, numerical modeling, and operational weather forecasting. He has published numerous articles on these topics in refereed journals, won numerous awards, and has served on national and international scientific committees. In addition to his research interests, he has been active throughout his career mentoring and increasing opportunities in the atmospheric sciences for underrepresented minorities.
For nearly a century, the AMS has been a national and international leader promoting and advancing topics relevant to the atmospheric and related sciences. Nonetheless, the continued evolution of our enterprise presents challenges for AMS to become more innovative in order to remain relevant in the modern world. Fundamental aspects of our enterprise are changing. Social media is already altering the way we identify, understand, and react to environmental hazards, through apps such as mPING. The coming Smart City revolution will further coat urban landscapes with a variety of new sensors providing unique insights into the functioning of the city at hyperlocal scales. Further integration of the social sciences will enable the enterprise to better understand how people interpret and use weather information. These are but a few of many examples where our changing world is providing both opportunity and stress to the weather enterprise.

As a whole, the real challenge is continuing to meet the requirements of the existing AMS—one that is thriving—while dramatically reinventing it to meet new challenges. As an AMS Councilor, my goals would be to confront this challenge by identifying and strengthening existing core activities of the AMS that are fundamental to our current success; recognizing and then changing ideas, practices, and attitudes that inhibit needed innovation; and converting breakthrough ideas from the membership into new avenues to increase effectiveness of the AMS enterprise.

SHELDON DROBOT

SHELDON DROBOT, Ph.D., MBA, is a senior analyst—competitive intelligence within the Environmental Solutions business unit of Harris Corporation’s Space and Intelligence segment. Space and Intelligence Systems offers complete Earth observation, weather, geospatial, space protection, and intelligence solutions from advanced sensors and payloads, ground processing, and information analytics. Drobot assumed the position in 2015 and is responsible for identifying critical environmental problems and leading strategic planning to help develop solutions.

Drobot earned his Ph.D. (2000) in geosciences (climatology focus) from the University of Nebraska, his B.A. (1995) and M.A. (1997) in geography from the University of Manitoba, and his MBA (2013) from the Leeds School of Business at the University of Colorado. After completing his doctoral degree, Drobot accepted a postdoctoral position within Aerospace Engineering at the University of Colorado, where he explored the use of autonomous aircraft for polar observations and developed seasonal sea ice forecasts. Following the postdoc, he transitioned to a science policy position with the National Academy of Sciences, staffing studies on developing climate data records from satellites, developing a vision for the 2007–09 International Polar Year, and devising a science plan for use of funds from the Exxon Valdez accident. In 2009, Drobot joined NCAR to lead the Maintenance Decision Support System and Connected Vehicle projects, both focused on advancing weather analytics for the transportation industry. The latter project led to creation of the patented Pikalert System, which combines vehicle data, such as wiper status and ABS condition, with traditional weather information to develop hyperlocal weather diagnostics and forecasts for drivers. He was invited to give a TEDx talk on Pikalert in 2013. During his time at NCAR, Drobot also participated in development of the Weather and Society Integrated Studies (WAS®IS) effort and helped develop the renewable energy forecasting program.

Drobot has served and promoted the atmospheric, transportation, and larger scientific communities through committee and conference participation and memberships in several organizations, including the AMS, National Weather Association, Intelligent Transportation Society of America, and the American Geophysical Union. He currently chairs the AMS Board on Enterprise Strategic Topics, which is located within the Commission on the Weather, Water, and Climate Enterprise.
TANJA FRANSEN (GOVERNMENT SECTOR)

AMS is an amazing organization, and as with many professional societies, communications and membership often present challenges. I’ve seen huge strides by AMS to improve communication with new tools and technologies. What I’d like to see is a way to better connect our 13,000 members, across the enterprise and across generations. How do we best attract millennials, and communicate with them? How do we take the talent of our seasoned members and use that to mentor and network so we learn from each other? For a few short years I dropped my membership to the AMS. I was out of college, starting a career, bills to pay, kids to clothe and feed, and I wasn’t really sure why a membership was important to me. What I didn’t consider at the time was the networking and mentoring that AMS offered. Attending my first Annual Meeting showed me the incredible talent and enthusiasm beyond my own sandbox. It was exciting to see the great research, operational best practices, and innovation of our members! My connections made through AMS have given me wonderful opportunities to interact and collaborate with the diverse membership, and I’d like to see that for all our members. Too often, new members, regardless of age and career, do not see all that AMS has to offer them. Annual Meetings are a great opportunity, but only about 25% of the membership directly benefits each year. Finding ways to connect members outside of conferences is something I would love to be a part of. If elected to serve, I would like to help AMS do that through continual improvements to how we connect people, as well as help grow the membership through outreach, mentoring, and networking. Thank you for this incredible opportunity to serve you, and make a difference.

TANJA FRANSEN

Tanja Fransen is the meteorologist-in-charge of the NOAA/National Weather Service in Glasgow, Montana, leading a talented team that provides weather, water, and climate services to northeast Montana. She was the warning coordination meteorologist there for 15 years prior to her current role, where she built relationships across government, private sector, academia, and media, and created educational and outreach programs. Impacts, decision support, and a Weather Ready Nation were her focus long before they became goals in strategic plans.

In 2005, she was accepted as a fellow to the original NCAR Weather and Society*Integrated studies (WAS*IS) program. This workshop greatly influenced her career as it connected the operational, research, and social science fields in ways that are now helping shape how the weather enterprise communicates hazards and risk. The experiences and connections from the workshop gave her opportunities to influence changes in decision support not just locally, but across the NWS and within the weather enterprise.

Fransen has served on the NOAA Education Council and the NWS Networking and Mentoring Committee, and she co-led the NWS Skywarn program. She’s been involved in numerous diversity projects, from promoting women in science to being on a recruitment and retention team. She currently serves as the cochair for the AMS Committee on Emergency Management and has cochaired the annual Major Weather Impacts session at the Annual Meeting for the past eight years. She was also a charter member of the AMS Board of Societal Impacts, is a member of the Montana Disaster and Emergency Services Association and the Glasgow Levee Committee, and is the former chairperson for the Montana EAS Committee.

She received her bachelor’s degree in Earth science: meteorology from the University of Northern Colorado in 1995, and has spent her 22-year NWS career in the High Plains. In 2014, she had the great honor of receiving the AMS Kenneth C. Spengler Award for leadership and innovation across the weather enterprise. She’s also received the NWS Isaac Cline Award for Leadership and the NOAA Administrator’s Award in 2011 for the development of the Cold Advisory for Newborn Livestock system. With the record snow and flood season in 2011, she was also named Montana’s “Hero for the Day” on the U.S. Senate floor by former U.S. Senator Max Baucus.
GARY GEERNAERT (GOVERNMENT SECTOR)

The AMS is well recognized for bridging basic research to innovation, in order to efficiently support the science and capability goals of the public and private sectors. Using themes of Annual Meetings and workshops, and policy statements issued on behalf of its members, federal agencies have valued the role that the AMS and its members have played. The AMS has also promoted agency coordination and collaboration, and it has documented major grand challenges to capture the imagination of policymakers. I am proud of the many successes that the AMS has facilitated since its founding.

In spite of AMS’s many successes, there are major changes we will all experience over the next decade that will influence agendas. Science is becoming more multidisciplinary; computational infrastructure is going through a paradigm shift with more sophisticated hardware and software; smart phones and other mobile platforms are collecting more complex environmental information; novel new materials and networks are revolutionizing sensor suites; and robotics and server-side analysis are becoming commonplace. The challenge for the AMS community over the next decade will be to exploit these opportunities yet maintain a culture where the process of discovery and risk-taking is preserved.

To prepare for the future, topics that are emerging as new priorities involve various combinations of (1) new science to enhance seamless weather and climate prediction; (2) multisector infrastructure risk analysis coupled to model ensembles; (3) economics, finance, health, and behavioral sciences as components of prediction frameworks; (4) uncertainty characterization; (5) codesign involving computer science, informatics, and communication networks; (6) miniaturized sensors, novel platforms, and communication networks that incorporate server-side analyses; and (7) revitalization of observing infrastructures. When posed as grand challenges for science, technology, and engineering, these sets of topics can succeed as part of the federal budget preparation and appropriations process only after significant engagement of scientists, engineers, and stakeholders working together as part of the same team. The AMS is perfectly positioned to serve this role.

As AMS marches into the next decade, it will be advantageous to strengthen relationships between federal laboratories, industry, and academia, exploit novel mentoring programs, and explore public–private partnerships across a wide swath of opportunities.

As a Councilor for the AMS, I will work hard to ensure that the AMS and its members have a significant role in contributing to the federal strategic science planning process, scientific discovery, expanded services, mentoring, and an expanded job market for both emerging and experienced professionals.
The American Meteorological Society has a rich history in curating the atmospheric sciences through activities deeply rooted in the core principals of the scientific process. AMS infrastructures have been significant enablers of our science, and these must remain central to the Society moving forward. However, our rapidly evolving scientific, technical, and societal environment poses several challenges to the Society. Two particular issues that I would undertake if elected to the AMS Council are broader membership of interdisciplinary professionals and enabling scientific advocacy.

The first issue is aimed at ensuring the Society serves the plurality of nonatmospheric science professionals that work in or are closely affiliated with our science. Of particular interest are technical practitioners responsible for the reduction of our science to practice in applications for the science and society. They tend to join our profession adjacently rather than organically, and therefore they are often not participating in or well served by the Society. While the AMS has historically supported hybrid disciplines, the AMS may not be keeping pace with its growth and diversification. As Councilor, I would encourage diversified membership via new discipline-specific ad hoc committees charged with recommending means to better incorporate these adjunct professionals into the Society.

The second challenge has to do with enabling effective advocacy for and by our profession on scientific issues including climate change. While the AMS is the leading representative on the science, for a number of very good reasons, the AMS does not directly engage in political advocacy. While I would not encourage that the AMS become an advocacy organization, I do believe that the Society can do more to catalyze, foster, and support such activities indirectly through its members and ancillary organizations. As a Councilor, I will promote such activities to the extent appropriate within the charter of our Society.
With the Society approaching its centennial, we must address not just new and emerging issues but also timeless ones. Meteorology has always been very relevant to society, but climate change has brought our field additional attention, often of an overtly political nature. In this situation, the Society’s reputation for integrity, hard-earned over the years, is now our strongest asset and must remain our guiding principle.

As Texas State Climatologist, I have learned that people have many different views and perceptions regarding climate change and its implications, but they all want us to tell them what the weather will be tomorrow. They may not trust the forecast, but they need to trust that the provider of that forecast is doing his or her best to tell them what they need to know. This trust in our profession must extend to the climate realm as well. The Society must continue to help its members identify and meet the weather- and climate-related needs of society at large, through science policy advocacy, network-building, and educational opportunities.

New technologies and social media will continue to offer options for fulfilling existing missions in a different way and for providing new services. To flourish, the Society must always benefit its individual and corporate members as well as the broader world. I would seek to ensure that the choices made by the Society in such critical areas as disciplinary and annual meetings, publications, and outreach are to the advantage of the broadest possible spectrum of members. The spirit of creativity that animated the Society’s founding 100 years ago must also animate us as we prepare to embark on the next 100 years.

John Nielsen-Gammon (Academic Sector)

John Nielsen-Gammon is Regents Professor of atmospheric sciences at Texas A&M University and serves as the Texas State Climatologist. He received his bachelor’s degree in Earth and planetary sciences (1984) and his master’s and doctoral degrees in meteorology (1987, 1990), all from the Massachusetts Institute of Technology. He joined the faculty at Texas A&M University in 1991 and was appointed State Climatologist by then-Governor George W. Bush in 2000.

Dr. Nielsen-Gammon has published on such diverse topics as sea breezes and coastal fronts, upper-level and low-level jets, air stagnation, extreme rainfall, data assimilation and parameter estimation, tornadic thunderstorms, tropical cyclogenesis, predictability, observing and analysis techniques, drought, and climate change. He has received two Editor’s Awards from AMS and reviewer citations from AGU and the American Society of Civil Engineers.

As State Climatologist, Dr. Nielsen-Gammon gives 20 to 50 invited talks a year to agricultural producers, water managers, natural resource professionals, trade organizations, and public interest groups throughout Texas on weather, climate, climate variability and change, and seasonal-to-interannual forecasting. He has been named a Weather Hero by the John C. Freeman Weather Museum and Outstanding Science Communicator by the Texas A&M Chapter of Sigma Xi.

Dr. Nielsen-Gammon joined the AMS in 1989 and was elected Fellow in 2011. He chaired the AMS Board on Higher Education from 2008 to 2011. He has twice served as program cochair of the AMS Student Symposium and was chair of the Drafting Committee for the AMS Statement on the Bachelor’s Degree in Atmospheric Sciences in 2010–11. Other professional activities include service as president of the International Commission for Dynamical Meteorology and as member of the Unidata Policy Committee and NSF/UCAR Observing Facilities Advisory Committee.
The AMS is a critically important institution for our field, unifying a diverse membership and continually redefining what it means to be an atmospheric, oceanic, or hydrologic scientist. I began my career as a theoretically oriented academic meteorologist, but my interests have broadened to include applied research on extreme weather risk, scientific communication, and interaction with the private sector. I now appreciate the AMS even more than I did before, and I am honored by the invitation to serve on the Council in this time of rapid change.

We face a political scene in which issues related to our science are urgently important, yet polarization and dysfunction often obscure the facts. We need to continually evaluate where AMS public statements or other outward-facing communications are needed, and how to make them effective. I believe that the AMS has a critical responsibility to speak on behalf of its membership about climate and weather issues that come before the public.

Though an academic myself, I believe strongly in the private sector’s importance in our field, and appreciate that the AMS explicitly embraces the private sector. In some of my own recent work I have been collaborating with a number of colleagues in the insurance industry and have found this very stimulating. On the Council I would look for ways to strengthen interactions between the private sector, academia, and government.

Finally, I believe publications will remain a challenging area for the AMS. Everything about the scientific publishing industry continues to change rapidly, including pressures toward open access as well as technological and economic changes. I see no simple solutions, but am interested to engage on this issue.
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*Cost for delivery outside of the U.S. is $40.95. Weatherwise is available to AMS Members through a cooperative agreement with Taylor & Francis Group LLC, the publishers of Weatherwise.
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**

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**2016**

**AUGUST**

Joint 21st American Meteorological Society (AMS) Satellite Meteorology, Oceanography and Climatology Conference and 20th AMS Conference on Air–Sea Interaction, 15–19 August, Madison, Wisconsin

Abstract deadline: 1 April 2016

Preregistration deadline: 1 July 2016

Manuscript deadline: 19 September 2016

Initial announcement published: June 2015

**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


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**2017**

**JANUARY**

16th Annual AMS Student Conference, 21–22 January, Seattle, Washington

Abstract deadline: 3 October 2016

Preregistration deadline: 15 December 2016


Fifth Annual AMS Conference for Early Career Professionals, 22 January, Seattle, Washington

Preregistration deadline: 15 December 2016

Initial announcement published: June 2016

*17th Presidential Forum, 22–26 January, Seattle, Washington

Preregistration deadline: 1 December 2016

Initial announcement published: TBD


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


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

Initial announcement published: May 2016

*An exhibit program will be held at this meeting.
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.
*12th Symposium on Societal Applications: Policy, Research and Practice, 22–26 January, Seattle, Washington
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

*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

*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: July 2016

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

*An exhibit program will be held at this meeting.
19th Conference on Middle Atmosphere, 26–30 June, Portland, Oregon
Abstract deadline: 1 March 2017
Preregistration deadline: 19 May 2017
Manuscript deadline: 26 July 2017

38th Conference on Radar Meteorology, 28 August–1 September, Chicago, Illinois
Abstract deadline: 11 May 2017
Preregistration deadline: 21 July 2017
Manuscript deadline: 15 September 2017

MEETINGS OF INTEREST
2016

AUGUST

30th Nordic Meteorological Meeting, 22–24 August, Stockholm, Sweden

SEPTEMBER

16th EMS Annual Meeting & 11th European Conference on Applied Climatology (ECAC), 12–16 September, Trieste, Italy

13th International Conference on Meteorology, Climatology and Atmospheric Physics (COMECAP 2016), 19–21 September, Thessaloniki, Greece

CLIVAR Open Science Conference, 19–23 September, Qingdao, China

The Geological Society of America Annual Meeting, 25–28 September, Denver, Colorado

MedCLIVAR 2016: Learning from the Past, Perceiving the Present, Engaging for the Future, 26–30 September, Athens, Greece

OCTOBER

Sixth Tri-State Weather Conference, 1 October, Danbury, Connecticut

NOAA’s 41st Climate Diagnostics and Prediction Workshop, 3–6 October, Orono, Maine

A Connected Ocean (ACO)/The Challenge of Observation Data Integration, 11–13 October, Brest, France

November

Northeast Regional Operational Workshop, 2–3 November, Albany, New York

International Meteorological Satellite Users’ Conference, 21–28 October, Songdo City, Incheon, Korea

Eighth EGU Leonardo Conference: From Evaporation to Precipitation—The Atmospheric Moisture Transport, 22–27 October, Ourense, Spain

April

EGU 2017 General Assembly, 23–28 April, Vienna, Austria

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CALL FOR PAPERS


The special one-day Symposium on Multi-Scale Atmospheric Predictability, sponsored by the American Meteorological Society, will be held on Wednesday, 25 January 2017, as part of the 97th AMS Annual Meeting in Seattle, Washington. Preliminary programs, registration, hotel, and general information will be posted on the AMS website (http://www.ametsoc.org/meet/annual/) in late September 2016.

With ever increasing computing resources, weather and climate prediction models have seen considerable improvements over the years through the use of increasingly fine resolutions with more accurate physics while ingesting more observations with increasingly advanced data assimilation techniques. Global convection-permitting models that seamlessly integrate weather and climate predictions from convective, mesoscale and synoptic to seasonal and intraseasonal scales are now within sight. In the meantime, the demands and expectations for more accurate forecasts at all scales are ever increasing.

Through a mix of invited and contributed presentations, this special one-day symposium solicits papers on recent progress and challenges in our current understanding of both the practical and intrinsic aspects of multi-scale atmospheric predictability for various weather and climate phenomena, including tornadic thunderstorms, mesoscale convective vortices, tropical cyclones, winter snowstorms, flooding, heat waves, droughts, MJOs, monsoons and EN-SOs. Practical predictability refers to the current capability of a forecast system or agency under best practice given state-of-the-art models with state-of-the-art initial and boundary conditions. Intrinsic predictability refers to the limit of prediction at different temporal and spatial scales given nearly perfect initial conditions and nearly perfect forecast models. Understanding the limits of intrinsic predictability is crucial in setting expectations and priorities for advancing deterministic forecasting (through better model, observing network and data assimilation) and in providing guidance on the design of advanced probabilistic and ensemble prediction.

The $95 abstract fee includes the submission of your abstract, the posting of your extended abstract, and the uploading and recording of your presentation which will be archived on the AMS website. Please submit your abstract electronically by 1 August 2016 (refer to the AMS webpage at http://www.ametsoc.org/meet/online_submit.html). The abstract fee (payable by credit card or purchase order) is charged at the time of submission (refundable only if abstract is not accepted).

Authors of accepted presentations will be notified via e-mail by late September 2016. All extended abstracts are to be submitted electronically and will be available online. Instructions for formatting extended abstracts will be posted on the AMS website. Authors have the option to submit manuscripts (up to 10 MB) electronically by 27 February 2017. All abstracts, extended abstracts, and presentations will be available on the AMS website at no cost.

For additional information please contact co-chairs, Fuqing Zhang, Penn State University (tel.: 814-865-0470; e-mail: fzhang@psu.edu), and Roberto Buizza, European Centre for Medium-Range Weather Forecasts (tel.: +44-118-9499653; e-mail: roberto.buizza@ecmwf.int). (8/16)

CALL FOR PAPERS

21st Conference on Atmospheric and Oceanic Fluid Dynamics, 26–30 June 2017, Portland, Oregon

The 21st Conference on Atmospheric and Oceanic Fluid, sponsored by the American Meteorological Society and organized by the AMS Committee on Atmospheric and Oceanic Fluid Dynamics, will be held 26–30 June 2017, jointly with the 19th Conference on Middle Atmosphere at the Portland Marriott Downtown Waterfront in Portland, OR. A preliminary program as well as registration, hotel, and general information will be posted on the AMS website (http://www.ametsoc.org) by early April 2017.

Papers are solicited in all areas of atmospheric and oceanic fluid dynamics spanning theory, observations, and modeling. We especially welcome papers describing idealized or process-based modeling studies. The AOFD committee would like to highlight three special sessions:

- Planetary Atmospheres and Oceans, including all aspects of fluid dynamics on planetary bodies other than Earth;
- Dynamics of Past and Future Climates, with a particular emphasis on conceptual models of changes in Earth’s climate;
- Ocean Submesoscale Dynamics

A full list of proposed sessions will be provided on the meeting website; the final session topics will be based on the number and topics of abstracts received.

We would also like to draw attention to two joint sessions with the Conference on Middle Atmosphere:

- Troposphere–Stratosphere Coupling
- Transport and Mixing.
For the former, abstracts exploring the coupling between the middle atmosphere and troposphere with the ocean are especially encouraged. Transport and mixing is an area where recent advances in our understanding of chemical and age transport in the middle atmosphere potentially connect with advances in chemical transport in the troposphere and biogeochemical transport in the oceans.

The deadline for abstract submission is 1 March 2017 (refer to the AMS webpage at http://www.ametsoc.org/meet/online_submit.html). 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, which will be archived on the AMS website. Authors of accepted presentations will be notified via e-mail by 10 April 2017. All extended abstracts are to be submitted electronically and will be available online. Instructions for formatting extended abstracts will be posted on the AMS website. Authors have the option to submit manuscripts (up to 10 MB) electronically by 26 July 2017. All abstracts, extended abstracts and presentations will be available on the AMS website at no cost.

The AOFD Committee of the American Meteorological Society (AMS) is proud to award Best Student Prizes at the 21st Conference on Atmospheric and Oceanic Fluid Dynamics. These awards recognize outstanding student contributions based on an evaluation of the oral or poster presentation; students should indicate they want to be considered for such awards at the time of abstract submission. Limited financial support is available for student participants. To apply, students should prepare a short written statement (no more than one page) declaring their financial need and circumstance, relevance of their research to the conference, and their background; a copy of the meeting abstract should also be provided. Applications should be sent in pdf format via e-mail to Ricky Sidla (e-mail: rsidla@ametsoc.org). Awardees may not receive any concurrent travel support from the AMS (e.g., an AMS travel grant). The selected students will be reimbursed by AMS (Ricky Sidla; e-mail: rsidla@ametsoc.org) following the meeting with the proper receipts. Applications will be accepted through 1 March 2017 and all applicants will be notified of their application status on or before 1 May 2017.

For additional information regarding the meeting, please contact one the program chairpersons: Gang Chen, Department of Atmospheric and Oceanic Sciences, University of California–Los Angeles (e-mail: gchenpu@ucla.edu; tel.: 310-206-9956); Juliana Dias, NOAA Earth System Research Laboratory, Physical Sciences Division, Boulder, Colorado (e-mail: juliana.dias@noaa.gov; tel.: 303-497-7235); Shafer Smith, Department of Mathematics, Courant Institute of Mathematical Sciences, New York University, New York, NY (e-mail: shafer@cims.nyu.edu; tel.: 212-998-3176); or Andrew Thompson, Department of Environmental Science and Engineering, California Institute of Technology, Pasadena, CA (e-mail: andrewt@caltech.edu; tel.: 626-395-8345). (8/16)

**CALL FOR PAPERS**

**19th Conference on Middle Atmosphere, 26–30 June 2017, Portland, Oregon**

The 19th Conference on Middle Atmosphere, sponsored by the American Meteorological Society and organized by the AMS Committee on Middle Atmosphere, will be held 26–30 June 2017, jointly with the 21st Conference on Atmospheric and Oceanic Fluid at the Portland Marriott Downtown Waterfront in Portland, OR. A preliminary program as well as registration, hotel, and general information will be posted on the AMS website (http://www.ametsoc.org) by early April 2017.

The 19th Conference on the Middle Atmosphere will focus on processes in the stratosphere and mesosphere, including their interactions with tropospheric weather and climate. Conference sessions are anticipated to focus on issues of relevance to the middle atmosphere, including expected signatures of climate change in middle atmospheric physical and chemical processes. An emphasis will be on advancing understanding of processes by the use of observations in conjunction with models of varying degrees of complexity. A full list of proposed sessions will be provided on the meeting website; the final session topics will be based on the number and topics of abstracts received.

We would like to special attention to two joint sessions with the Conference on Atmospheric and Oceanic Fluid Dynamics:

- **Troposphere–Stratosphere Coupling**
- **Transport and Mixing**

For the former, abstracts exploring the coupling between the middle atmosphere and troposphere with the ocean are especially encouraged: the majority of comprehensive climate models now represent the atmosphere from the top of the stratosphere to the bottom of the ocean, opening up the potential for new phenomena and theory. Transport and mixing is an
area where recent advances in our understanding of chemical and age transport in the middle atmosphere potentially connect with advances in chemical transport in the troposphere and biogeochemical transport in the oceans. This session will provide a forum for theoreticians focused on the same problem but approaching it from varying components of the climate system.

Please submit your abstract electronically via the web by 1 March 2017 (refer to the AMS webpage at http://www.ametsoc.org/meet/online_submit.html). 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 fee includes the submission of an abstract, the posting of an extended abstract, and the recording of your presentation, to be archived on the AMS website.

We anticipate that authors of accepted presentations will be notified via e-mail by 10 April 2017. All extended abstracts are to be submitted electronically and will be available on-line via the web. Instructions for formatting extended abstracts will be posted on the AMS website. Authors have the option to submit manuscripts (up to 10 MB) electronically by 26 July 2017. All abstracts, extended abstracts and presentations will be available on the AMS website at no cost.

The Middle Atmosphere Committee is excited to award best student presentation prizes to recognize outstanding student oral and poster presentations. Students are asked at the time of the abstract submission if they want to be considered for such awards.

For additional information please contact the program chairs, Natalia Calvo (e-mail: nataliac@fis.ucm.es) and Margaret Hurwitz (e-mail: margaret.m.hurwitz@nasa.gov), or committee members Alan Plumb (e-mail: plumb@mit.edu) or Nicholas Davis (e-mail: ndcodeblue@gmail.com). (8/16)

CALL FOR PAPERS
38th Conference on Radar Meteorology, 28 August–1 September 2017, Chicago, IL

The 38th Conference on Radar Meteorology, sponsored by the American Meteorological Society and organized by the AMS Committee on Radar Meteorology, will be held 28 August–1 September 2017 at the Swissotel Downtown, Chicago, IL. A preliminary program, registration, hotel, and general information will be posted on the AMS website (http://www.ametsoc.org) by 20 June 2017. The theme for this year’s conference is “At the crossroads of engineering and science: Using radar-based observations to improve our understanding of the atmosphere and advance prediction across spatial and temporal scales.”

Papers for this conference are solicited on the following areas:

• New and emerging radar technology: advances in radar hardware, advances in signal/array processing, innovative applications of radar, integrating new technologies in field campaigns, polarimetric phased array radar, solid-state and pulse compression radar, homogeneous adaptive radar networks, and innovation in education and training;
• Radar networks, quality control, processing and software: topics covering the operation of radars ensuring the best quality products; novel aspects of quality control processing; and software packages, including emerging approaches in processing and extraction of insight from radar systems.
• Quantitative precipitation estimation and hydrology: new techniques for rain accumulation estimation, error analysis, multisensor, and blended approaches (gauges, microwave links, and radiometer); coupling of radar estimates to hydrological models; and long-term climatologies and case studies;
• Microphysical studies with radars: radar-based or multisensor estimation of microphysical properties of cloud and precipitating ice and liquid; identification of microphysical processes in radar moments, polarimetric measurements, and radar Doppler spectra; long-term statistical studies and seasonal variation; and error structure and validation with in situ and complementary measurements.
• Organized convection and severe phenomena: studies of impactful events including multi-instrument and multi-platform retrievals (e.g., multi-Doppler), covering many scales from tornadoes and microbursts to winter events and hurricanes;
• Use of radar data for nowcasting and numerical models: nowcasting, assimilation of radar data into convective scale models, assimilation of measurements, use of radar data for convective scale model validation and microphysics improvement, combined use of radar and satellite data in NWP models, automated data quality and analysis tools for NWP models, convective-scale ensemble prediction involving radar, optimal scanning strategies, warn-on-forecast, and use of radar and wind profilers in LES scale models.
• Moving platforms—vehicle, airborne, shipborne and spaceborne: the study of atmospheric phenomena from moving platforms including manned and unmanned aircraft, current, and future spaceborne platforms and shipboard radar systems, which covers technological aspects, case studies, and ground validation exercises.

• Cloud studies using radars: observations of low reflectivity targets including clouds and drizzle, millimeter wavelength radars and synergistic observations including lidar/radar-, multiwavelength-, and spectral-based studies

• Studies of non-hydrometeorological returns: studies on non-hydrometeor returns such as biological targets, clear air, and boundary layer structure and density currents such as cold pools and frontal zones.

The $95 abstract fee includes the submission of your abstract, the posting of your extended abstract, and the uploading and recording of your presentation, which will be archived on the AMS website.

This year some financial assistance will be made available to students attending the conference to offset the cost of registration. Interested students should contact the conference chairs Scott Ellis on submission of their abstract, and application details will be forwarded on abstract acceptance. In addition, students should visit the AMS website (https://www.ametsoc.org/ams/index.cfm/information-for/students/ams-student-travel-grants/) for details on travel grants for students attending and not presenting a paper.

Exhibitors are solicited to participate in the conference by purchasing AMS exhibit booth space and presenting their latest technologies and advancements. Exhibitors at this meeting will have the opportunity to submit an abstract for a tentatively planned vendor session. Limited spots are available. Interested exhibitors who have returned a signed contract to AMS should send their title, presenter contact information, and abstract text to Jenn Rosen (e-mail: jrosen@ametsoc.org) by 1 May 2017.

Please submit your abstract electronically by 11 May 2017 (refer to the AMS webpage at http://www.ametsoc.org/meet/online_submit.html). The abstract fee (payable by credit card or purchase order) is charged at the time of submission (refundable only if abstract is not accepted).

The best student oral presentation and poster presentation will be awarded the Spiros G. Geotis Prize. Students need to indicate their intent to participate in this competition when they submit their abstract.

Authors of accepted presentations will be notified via e-mail by 16 June 2017. All extended abstracts are to be submitted electronically and will be available online. Instructions for formatting extended abstracts will be posted on the AMS website. Authors have the option to submit manuscripts (up to 10 MB) electronically by 15 September 2017. All abstracts, extended abstracts and presentations will be available on the AMS website at no cost.

For additional information please contact the program chairpersons, Scott Collis (e-mail: scollis@anl.gov) and Scott Ellis (e-mail: sellis@ncar.edu). (8/16)
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.

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
- 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
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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.
The Life Cycles of Extratropical Cyclones

Edited by Melvyn A. Shapiro and Sigbjørn Grønås

Containing expanded versions of the invited papers presented at the International Symposium on the Life Cycles of Extratropical Cyclones, held in Bergen, Norway, 27 June–1 July 1994, this monograph will be of interest to historians of meteorology, researchers, and forecasters. The symposium coincided with the 75th anniversary of the introduction of Jack Bjerknes’s frontal-cyclone model presented in his seminal article, “On the Structure of Moving Cyclones.” The monograph’s content ranges from a historical overview of extratropical cyclone research and forecasting from the early eighteenth century into the mid-twentieth century, to a presentations and reviews of contemporary research on the theory, observations, analysis, diagnosis, and prediction of extratropical cyclones. The material is appropriate for teaching courses in advanced undergraduate and graduate meteorology.

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The Earth Science Office at Marshall Space Flight Center in Huntsville, Alabama, is soliciting statements of interest for full-time Ph.D. level civil service scientist positions for early- and mid-career positions in the following areas:

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We seek a scientist with expertise in performing basic and applied research that uses NASA remote sensing assets of precipitation (e.g., GPM) or land surface (e.g., SMAP, derived MODIS products, ASTER, Landsat) exclusively or in conjunction with other domestic and international mission sensors for improving hydrologic, streamflow, or land surface models. Expertise may also be demonstrated in use of current missions or simulated data sets as precursors to upcoming NASA instruments (e.g., GRACE-FO, SWOT, NISAR, HySPR, ECOSTRESS). Candidates should have (at a minimum) expertise using land surface models (e.g., Noah, Noah-MP) and hydrologic models (e.g., VIC, CREST, WRF-Hydro) and ideally have experience in using these models with coupling to a regional or global numerical weather prediction system.

Atmospheric Remote Sensing
We seek a scientist with expertise in atmospheric remote sensing and experience in development of new remote sensing products from infrared and passive microwave sensors to support scientific study and transition to operational customers. Developed products will target applied research to demonstrate forecast improvements in support of transition to operations activities of the Earth Science Office. Products developed are expected to make use of new sensors that represent state-of-the-science observing platforms for Earth’s atmospheric processes at improved resolution and/or accuracy compared to predecessor sensors. Expertise in the study of atmospheric processes including convection, clouds/precipitation, atmospheric dynamics, and dust/aerosols, and coordination/communication with end users (e.g., NOAA/NWS, EPA, etc.) is desired.

Radio Frequency Engineer for Microwave Remote Sensing
We seek an Earth Science microwave remote sensing engineer experienced in the design, development and integration of active and/or passive microwave instruments for multi-frequency (0.5 GHz–500 GHz) airborne and satellite remote sensing of the earth’s atmosphere, hydrosphere, cryosphere and biosphere. Qualified candidates will possess a combination of skills ranging from advanced antenna design to include patch-panels and AESA technologies, digital receiver/transmitter design and electronics, digital signal processing, imaging techniques to include both synthetic and real apertures, data storage/handling, and instrument calibration. Also highly desired are systems engineering skills and a demonstrated ability to effectively translate between earth system science requirements for field and science applications and instrument calibration and imaging requirements.

Climate Science
We seek a scientist with expertise in dynamical modeling and diagnostic analysis of water and energy flux processes relevant to the climate system on regional to global scales and at intra-seasonal to decadal time scales. The successful candidate will demonstrate a strong background in combining satellite retrievals, reanalysis data, and global/regional modeling perspectives in addressing connections between physical processes and intraseasonal to decadal climate variability. In particular, skill in combining current and emerging NASA capabilities to measure and validate climate system processes and feedbacks is strongly desired. The ability to collaborate closely with ocean and land modeling colleagues in the design, execution and interpretation of climate model experiments using the NASA GEOS model system and NASA high performance computing capabilities is desired.

Applications of Synthetic Aperture Radar
We seek a scientist with expertise and demonstrated experience in Earth Science remote sensing using synthetic aperture radar (SAR) technologies from airborne of satellite platforms for scientific studies and end user applications. Knowledge of SAR instrument technologies (orbital and/or sub-orbital), measurement techniques (e.g., polarimetry, inSAR), and broad experience in the application of the data to surface remote sensing problems for hydrologic, agricultural, and disaster applications is highly desired.

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We seek a scientist with expertise in active and/or passive microwave remote sensing of snow as it falls from the atmosphere, terminates on the land surface, and becomes stored as water content in the form of snowpack. The candidate will possess a robust understanding of snow physical properties, retrieval of those properties using remote sensing, and coupling of those properties to surface hydrologic and climate processes.

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