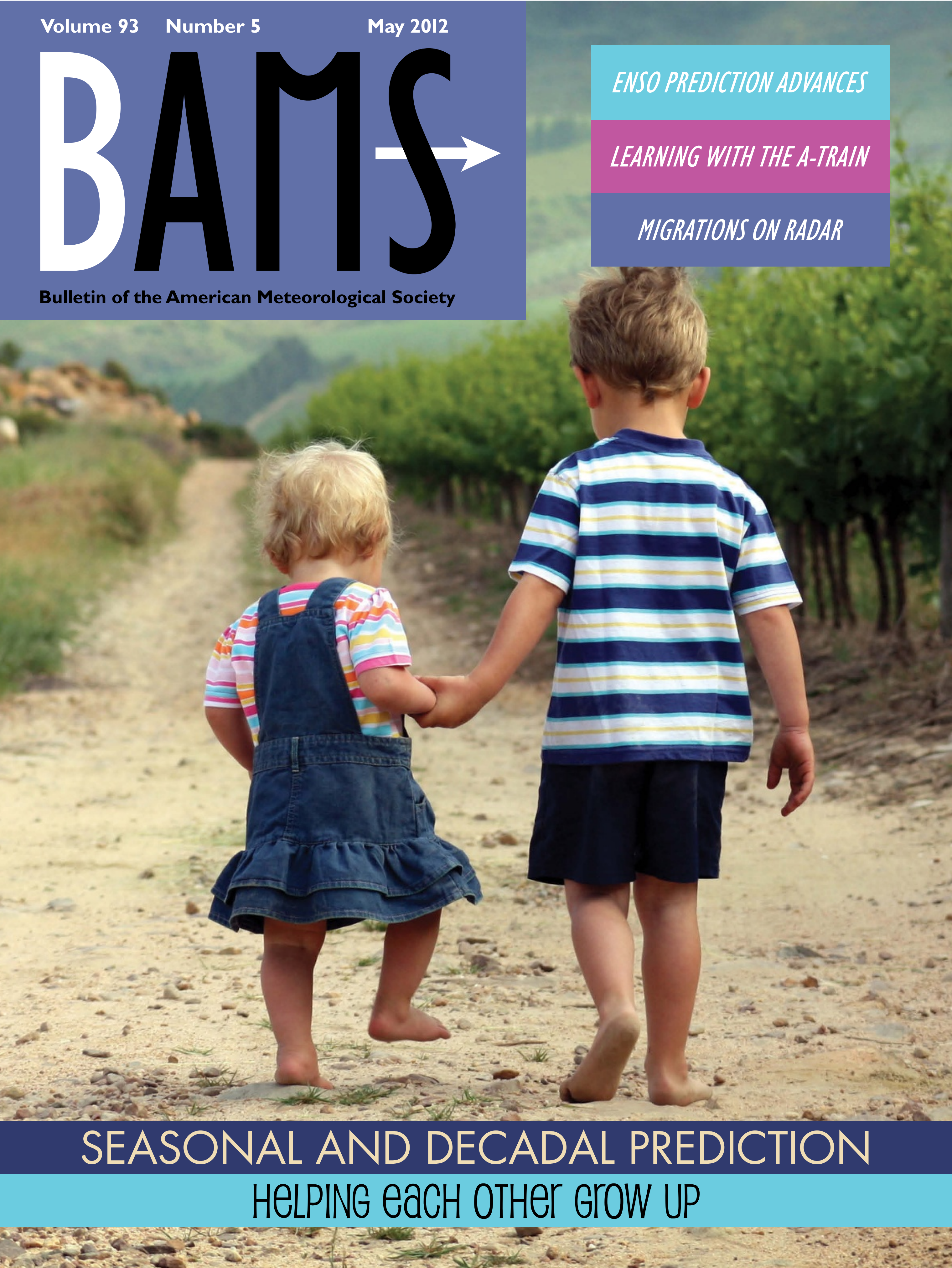
Volume 93 Number 5 May 2012

BAMS

Bulletin of the American Meteorological Society



ENSO PREDICTION ADVANCES

LEARNING WITH THE A-TRAIN

MIGRATIONS ON RADAR

SEASONAL AND DECADAL PREDICTION

HELPING EACH OTHER GROW UP

BAMS

Bulletin of the American Meteorological Society

VOLUME 93, NUMBER 5, MAY 2012

Supplements are available online at http://journals.ametsoc.org/toc/bams/93/5.

ON THE COVER

In the family of prediction services, seasonal and decadal products are the youngsters: the former is well established but still maturing, and the latter is just getting started. Goddard et al. argue that investment in either time scale of prediction should inevitably help its sibling develop, too. For more, see the essay by Goddard beginning on page 621.

CONTENTS

NOWCAST

45 BEACON

DEPARTMENTS

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.

The *Bulletin of the American Meteorological Society* (ISSN 0003-0007) is published monthly by the American Meteorological Society, 45 Beacon St., Boston, MA 02108-3693. Periodical postage paid at Boston, MA, and at additional mailing offices. Subscription price to members is included in annual dues. Subscription price to nonmembers is available on request; single issues are $12.50 each for members, $20 for nonmembers (prices incl. shipping and handling). Address all business communications to the Executive Director, AMS, 45 Beacon St., Boston, MA 02108-3693 (617-227-2425). POSTMASTER: Send address changes to *Bulletin of the American Meteorological Society*, 45 Beacon St., Boston, MA 02108-3693.

LETTER FROM THE EDITOR: ASKING THE RIGHT QUESTIONS

Many people are celebrating the ongoing upgrades of the NEXRAD radar network to dual polarization capabilities. Across the nation the loudest cheering we've heard has been from severe weather forecasters as they've gained the ability to distinguish hail from raindrops when they look at their radar readouts. But how many of us noticed the faint but unmistakable popping of champagne corks in the ecology community?

Radar is useful for tracking creatures taking wing in search of food—or to avoid predators. Apparently, dual polarization in particular is useful for distinguishing, say, bats from insects; hence the revelry about radar upgrades. Actually, weather radar has long helped ecologists, even without dual polarization. In this issue, Chilson et al. (page 669) describe how, with little fanfare in the meteorological community, radar experts have been working with ecologists to develop algorithms to separate out the signatures of various species. They're even using tethered bats in labs to make it possible to use radar to identify the size and quantities of different flying species.

This is clearly a case of the enhanced capabilities available to meteorologists when working closely with their clientele. If you don't know biologists and ecologists, don't know what they're thinking, or what they're asking, then you'll probably never realize what you can do for (or with) them. I'm reminded of the adage, "Experts know all the answers—if you ask them the right questions." Even highly educated scientists from other fields need help knowing what questions to ask of meteorology.

This is why it is encouraging to read (page 697) that John Lanicci is teaching Embry-Riddle undergraduates to analyze the decision-making processes of their clients as part of an introductory course in weather forecasting. The lesson from Chilson's article is even more true for forecasters than researchers. Understanding the person who will use the forecast informs the forecast, just as understanding the forecaster will improve use of the forecast. Lanicci shows it is never too early to think of forecasting this way: in terms of a full business-process model.

Lanicci teaches students to categorize a forecast user's intentions. It's another example of asking the right questions of the experts. People readily use forecasts to mitigate risks and protect resources from weather and climatic threats, but too often they fail to use forecasts to *exploit* the opportunities weather presents. Reacting to well-known, immediate questions of danger and safety crowds out opportunities for new avenues of collaboration with meteorologists. Exploiting weather is not going to happen without clear understanding between forecasters and forecast users.

It's this clear understanding that enables Chilson et al. to call existing NEXRAD data at the National Climatic Data Center "one of the largest biological data archives in the world." What a delight it is, for instance, to find out that radar studies of aerial behavior can give ecologists important information about ecosystems not just in the air but, surprisingly, on the ground as well. The information we seek is not always where we expect it, but scientists will find it if they're asked (or asking) the right questions.

—*Jeff Rosenfeld,* Editor-in-Chief

ABSTRACTS

SKILL OF REAL-TIME SEASONAL ENSO MODEL PREDICTIONS DURING 2002–11: IS OUR CAPABILITY INCREASING?

Real-time model predictions of ENSO conditions during the 2002–11 period are evaluated and compared to skill levels documented in studies of the 1990s. ENSO conditions are represented by the Niño-3.4 SST index in the east-central tropical Pacific. The skills of 20 prediction models (12 dynamical, 8 statistical) are examined.

Results indicate skills somewhat lower than those found for the less advanced models of the 1980s and 1990s. Using hindcasts spanning 1981–2011, this finding is explained by the relatively greater predictive challenge posed by the 2002–11 period and suggests that decadal variations in the character of ENSO variability are a greater skill-determining factor than the steady but gradual trend toward improved ENSO prediction science and models. After adjusting for the varying difficulty level, the skills of 2002–11 are slightly higher than those of earlier decades.

Unlike earlier results, the average skill of dynamical models slightly, but statistically significantly, exceeds that of statistical models for start times just before the middle of the year when prediction has proven most difficult. The greater skill of dynamical models is largely attributable to the subset of dynamical models with the most advanced, high-resolution, fully coupled ocean–atmosphere prediction systems using sophisticated data assimilation systems and large ensembles. This finding suggests that additional advances in skill remain likely, with the expected implementation of better physics, numeric

ABSTRACTS

and assimilation schemes, finer resolution, and larger ensemble sizes. *(Page 631)*

SINGLE AIRCRAFT INTEGRATION OF REMOTE SENSING AND IN SITU SAMPLING FOR THE STUDY OF CLOUD MICROPHYSICS AND DYNAMICS

Clouds are a critical component of the Earth's coupled water and energy cycles. Poor understanding of cloud–radiation–dynamics feedbacks results in large uncertainties in forecasting human-induced climate changes. Better understanding of cloud microphysical and dynamical processes is critical to improving cloud parameterizations in climate models as well as in cloud-resolving models. Airborne in situ and remote sensing can make critical contributions to progress. Here, a new integrated cloud observation capability developed for the University of Wyoming King Air is described. The suite of instruments includes the Wyoming Cloud Lidar, a 183-GHz microwave radiometer, the Wyoming Cloud Radar, and in situ probes. Combined use of these remote sensor measurements yields more complete descriptions of the vertical structure of cloud microphysical properties and of cloud-scale dynamics than that attainable through ground-based remote sensing or in situ sampling alone. Together with detailed in situ data on aerosols, hydrometeors, water vapor, thermodynamic, and air motion parameters, an advanced observational capability was created to study cloud-scale processes from a single aircraft. The Wyoming Airborne Integrated Cloud Observation (WAICO) experiment was conducted to demonstrate these new capabilities and examples are presented to illustrate the results obtained. *(Page 653)*

PARTLY CLOUDY WITH A CHANCE OF MIGRATION: WEATHER, RADARS, AND AEROECOLOGY

Aeroecology is an emerging scientific discipline that integrates atmospheric science, Earth science, geography, ecology, computer science, computational biology, and engineering to further the understanding of biological patterns and processes. The unifying concept underlying this new transdisciplinary field of study is a focus on the planetary boundary layer and lower free atmosphere (i.e., the aerosphere), and the diversity of airborne organisms that inhabit and depend on the aerosphere for their existence. Here, we focus on the role of radars and radar networks in aeroecological studies. Radar systems scanning the atmosphere are primarily used to monitor weather conditions and track the location and movements of aircraft. However, radar echoes regularly contain signals from other sources, such as airborne birds, bats, and arthropods. We briefly discuss how radar observations can be and have been used to study a variety of airborne organisms and examine some of the many potential benefits likely to arise from radar aeroecology for meteorological and biological research over a wide range of spatial and temporal scales. Radar systems are becoming increasingly sophisticated with the advent of innovative signal processing and dual-polarimetric capabilities. These capabilities should be better harnessed to promote both meteorological and aeroecological research and to explore the interface between these two broad disciplines. We strongly encourage close collaboration among meteorologists, radar scientists, biologists, and others toward developing radar products that will contribute to a better understanding of airborne fauna. *(Page 669)*

METEOROLOGICAL EDUCATION AND TRAINING USING A-TRAIN PROFILERS

NASA A-Train vertical profilers provide detailed observations of atmospheric features not seen in traditional imagery from other weather satellite data. *CloudSat* and *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (*CALIPSO*) profiles vividly depict the vertical dimension of otherwise two-dimensional features shown in mapped products. However, most forecasters have never seen these profiles and do not appreciate their capacity to

SEND US YOUR THOUGHTS

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

convey fundamental information about cloud and precipitation systems. Here, these profiles are accompanied by weather satellite images and explained in the context of various meteorological regimes. Profile examples are shown over frontal systems, marine stratocumulus, orographic barriers, tropical cyclones, and a severe thunderstorm. *(Page 687)*

USING A BUSINESS PROCESS MODEL AS A CENTRAL ORGANIZING CONSTRUCT FOR AN UNDERGRADUATE WEATHER FORECASTING COURSE

For the last five years, the author has employed a business process model as a central organizing construct for the senior-level Forecasting Techniques course at Embry-Riddle Aeronautical University's Daytona Beach, Florida, campus. The process model allows weather analysis and forecasting to be examined as both a scientific process and a business operation, with emphasis on employing a user-focused approach. The use of the model arose from the need for an organizing context for the students, mostly seniors applying their knowledge from previous coursework, most of whom are learning to make their first weather forecasts. The process model used in the present version of the course evolved from one originally developed by the U.S. Air Force to describe weather information's value-added contributions to daily operations. The model consists of two major interrelated components: the weather information processing cycle (WIPC) and the provider–user relationship (PUR). The WIPC describes the analysis/forecast process from the scientific point of view, whereas the PUR examines the relationship between the provider and user of meteorological information. The WIPC uses familiar concepts such as data collection, analysis, and prediction, whereas the PUR introduces the students to complex (and seldom taught) topics such as user requirements and mission analyses. The process model also provides a framework for the final project, a case-study analysis that emphasizes not only the weather associated with the event but also its resulting impact on the affected population. *(Page 697)*

Could Newly Discovered Particle Slow Warming?

An atmospheric molecule that was recently observed for the first time could be a key player in stifling current rising temperatures on Earth. Criegee biradicals (also known as Criegee intermediates) are invisible, short-lived, and highly reactive molecules that oxidize pollutants—such as nitrogen dioxide and sulfur dioxide—created during combustion reactions. By breaking down these pollutants into sulfates and nitrates, Criegee biradicals facilitate the creation of aerosols; because aerosols play a key role in cooling Earth by reflecting incoming solar radiation, the research suggests that the biradicals, which occur naturally but could also be produced in a laboratory, might ultimately be used to fight global warming.

Criegee biradicals were originally posited by German chemist Rudolf Criegee in the 1950s, but they had never actually been detected until now. Using specially designed equipment—including a mass spectrometer that can weigh each individual molecule that is produced—and the intense light source from a third-generation synchrotron facility, researchers from the University of Manchester, the University of Bristol, and Sandia National Laboratories observed chemical reactions and were able to detect the formation and removal of various isomers (molecules that contain the same atoms bonded in different ways). They discovered that a reaction between oxygen and the iodomethyl radical CH_2I led to the formation of formaldehyde oxide (CH_2OO), a gas-phase Criegee intermediate that had previously been determined to form through a different chemical reaction. Upon observing its alternate formation, they were able to measure the newly detected chemical intermediate's reaction with water, sulfur dioxide, nitric oxide, and nitrogen dioxide, and their observations showed that Criegee biradicals react more rapidly than previously believed and quicken the formation of sulfate and nitrate in the atmosphere.

"Criegee radicals have been impossible to measure until this work," says study coauthor Carl Percival of the University of Manchester. "We have been able to quantify how fast Criegee radicals react for the first time. The main source of these Criegee biradicals does not depend on sunlight and so these processes take place throughout the day and night."

MOTHER NATURE WINS OLYMPIC GOLD

Prior to the 2008 Summer Olympics, China had the Herculean task of cutting Beijing's air pollution in preparation for the games. They succeeded, reducing pollution up to 50 percent by limiting driving, stopping pollution-producing manufacturing and power plants, and even moving heavy polluting industries. New research from the Department of Energy's Pacific Northwest National Laboratory indicates that while this did help cut emissions, the weather may have played just as large a role in the cleanup of the air over the city. According to atmospheric chemist Xiaohong Liu, rain and wind were likely responsible for about half the cleanup. "The weather was very important in reducing pollution. You can see the rain washing pollution out of the sky and wind transporting it away from the area," he says. To find out if the pollution controls were successful, the researchers modeled pollution and weather conditions before, during, and after the Olympic Games. They found that emission sources dropped up to a half in the week just before and during the Olympics, noting that while some pollution was washed out by rain, most of it got blown away by wind. More importantly, they found that the wind direction was critical to clearing the sky, with the north wind from the mountains during the Games keeping pollution from urban areas 50 miles to the south at bay. The researchers stress that this portion of their results indicates that emission controls need to expand beyond the local area in order to be most effective. (Source: DOE/Pacific Northwest National Laboratory)

The researchers noted that future studies will take advantage of the ability to manufacture Criegee biradicals and could eventually have significant implications for mitigating current warming of the Earth. The research was recently published in *Science*. (SOURCE: University of Manchester]

SURVEY: INDIA'S AIR IS WORLD'S UNHEALTHIEST

According to the biannual Environmental Performance Index (EPI), India's air is the most harmful to human health in the world. Atmospheric levels of fine particulate matter, or PM 2.5, in the rapidly industrializing nation of 1.2 billion people are almost 5 times higher than the unsafe limit for humans.

This year's EPI ranks 132 nations overall, as well as in each of 10 categories: environmental health, agriculture, biodiversity and habitat, climate change and energy, fisheries, forests, water (ecosystem effects), air (ecosystem effects), water (human health effects), and air (human health effects). Each country is given a weighted score from 1 to 100 and is then ranked.

India's score of 3.73 in the air (human health effects) category was significantly lower than the second-to-last country on the list, Bangladesh. The next lowest were Nepal, Pakistan, and China, respectively. At the opposite end of the list, 45 countries (including the United States) received a perfect score of 100 in this category.

The index is compiled by the Yale Center for Environmental Law and Policy and Columbia University's Center for International Earth Science Information Network (CIESIN). The 2012 version is the seventh iteration of the rankings, and its methodology was enhanced from previous versions by focusing on a smaller set of core indicators that meet higher standards, including direct measurement through satellite observation (rather than modeled data) and consistent time series.

The 2012 EPI ranked Switzerland number 1 with the highest overall EPI score, followed by Latvia, Norway, Luxembourg, and Costa Rica. The lowest score went to Iraq, followed by Turkmenistan, Uzbekistan, Kazakhstan, and South Africa. The United States was ranked 49th and India was 125th, overall.

For complete rankings and more information on the EPI, go to www.epi.yale.edu.

Cold Plasma Abundant in Upper Atmosphere

Low-energy (cold) ions have long been elusive to atmospheric researchers, especially at high altitudes. Forming in Earth's ionosphere, they traditionally have been very difficult to detect amid a steady stream of high-energy ions from the solar wind, thus stifling observation of the cold ions and inhibiting our understanding of their influence on space weather. But a new study in *Geophysical Research Letters* has brought the cold ions to light and revealed they are much more plentiful in Earth's magnetosphere than was previously believed.

Utilizing one of the four spacecraft of the CLUSTER II mission, researchers taking measurements with the onboard electric field detector at altitudes of 20,000–100,000 km noticed strong electric fields in unanticipated locations, as well as other oddities in the measurements.

ECHOES

"It's a win-win situation, because the sulfate can be taken out of the fuel to improve air quality around airports and, at the same time, it's not going to have a detrimental impact on global warming."

—Nadine Unger of Yale University, on a recent study in *Geophysical Research Letters* that shows the removal of sulfur from airplane fuel has a cooling effect on the atmosphere. Sulfur emissions, which can be harmful to the lungs and cardiovascular system, are abundant in the air around airports, but efforts to reduce their levels in aviation fuel have been countered by the belief that such a reduction would cause an increase in atmospheric temperature because sulfate particles reflect solar radiation back into space. The new research used a global-scale model to study the effect of reducing sulfur amounts in jet fuel from 600 to 15 milligrams per kilogram of fuel, which is the level targeted by the U.S. Department of Transportation. The study found that nitrates, which are created from nitrogen oxides in jet exhaust, interact with the sulfur and become more plentiful when the sulfate levels decrease; since nitrates also deflect solar radiation, the net result of a reduction of sulfur levels is a slight cooling of the atmosphere. (Source: Yale University)

"To a scientist, it looked pretty ugly," explains study coauthor Mats André of the Swedish Institute of Space Physics. "We tried to figure out what was wrong with the instrument. Then we realized there's nothing wrong with the instrument."

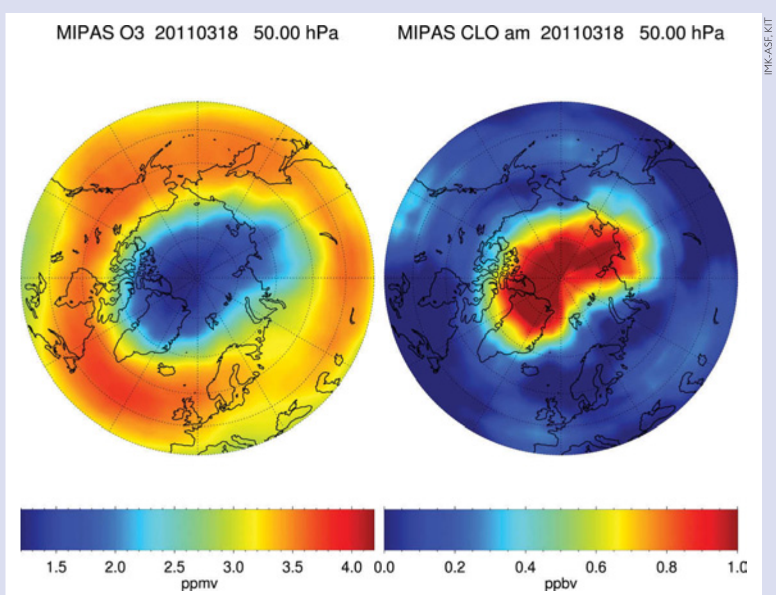
In fact, André and coauthor C. M. Cully found that a plasma of cold ions was changing the structure of the electrical fields the spacecraft was measuring. And that led to the discovery of far more cold ions than expected, considering the large amounts of hot plasma (high-energy ions) that are brought into the upper atmosphere by the solar wind. The scientists discovered that 50%–70% of the time, the cold plasma makes up most of the mass in huge regions of space. In some locations, these ions are predominant almost all of the time. André and Cully calculated that about one kilogram of cold plasma leaves Earth's atmosphere every second.

"The more you look for low-energy ions, the more you find," says André, who is a professor of space physics and leader of the research team. "We didn't know how much was out there. It's more than even I thought."

Determining the amounts of cold plasma in the atmosphere could help scientists better understand the atmospheric characteristics of other planets and moons. It may also be valuable in space weather forecasting. While high-energy hot plasma is directly responsible for generating space weather, including solar storms, the cold-energy ions are believed to influence space weather in some way, and improved data on their atmospheric distribution could help make forecasting such weather more accurate. (Source: American Geophysical Union)

Cold Temperatures Spurred Arctic Ozone Hole

During winter 2010–11 and for the first time ever, an ozone hole opened over the Arctic region, and it was comparable in its extent to the Antarctica-sized hole that appears annually over the South Pole. To determine the cause of this new ozone hole, scientists from the Karlsruhe Institute of Technology in Germany studied satellite measurements of the chemical composition of the atmosphere above the Arctic and compared them to chemical transport model calculations. They found that the extreme cold temperatures of 2010–11 exacerbated the effects of chlorofluorocarbons over the Arctic and induced the growth of the hole through the large-scale decimation of ozone in the lower stratosphere. Over the past 30 years, winter temperatures in this layer of the atmosphere over the Arctic have gotten about 1°C cooler on average per decade. The new research, published recently in *Geophysical Research Letters*, suggests that a continuation of this trend could lead to a regular wintertime breakdown of the ozone layer over the region. "We found that [a] further decrease in temperature by just 1°C would be sufficient to cause a nearly complete destruction of the Arctic ozone layer in certain areas," notes Björn-Martin Sinnhuber, lead author of the study. The figure below, from March 2011, illustrates the cause and effect: To the right (in red) is a clear increase in the concentration of chlorine monoxide, which is directly involved in destroying ozone. To the left, in dark blue, is a significant reduction in ozone values centered on the North Pole. (Source: Helmholtz Association of German Research Centres)



THE EWIEM NIMDIE SUMMER SCHOOL SERIES IN GHANA

Capacity Building in Meteorological Education and Research—Lessons Learned and Future Prospects

BY ADRIAN M. TOMPKINS, DOUGLAS J. PARKER, SYLVESTER DANOUR, LEONARD AMEKUDZI, CAROLINE L. BAIN, ABDUL DOMINGUEZ, MICHAEL W. DOUGLAS, ANDREAS H. FINK, DAVID I. F. GRIMES, MATTHEW HOBBY, PETER KNIPPERTZ, PETER J. LAMB, KATHRYN J. NICKLIN, AND CHARLES YORKE

THE EWIEM NIMDIE SUMMER SCHOOL CONCEPT. The Ewiem Nimdie summer school is a biennial or triennial event that to date has been hosted in Ghana and focuses on the atmospheric sciences; "Ewiem Nimdie" means "atmospheric science" in the local Ashanti language. The first school was conducted in the summer of 2008, hosted by the Kwame Nkrumah University of Science and Technology (KNUST) located in Kumasi, with the second school taking place at the same institution two years later, in July 2010. The schools were designed to help launch the undergraduate meteorology program of KNUST and benefited from the significant increase in research activity regarding West African weather and climate that has arisen from the African Monsoon Multidisciplinary Analysis (AMMA) program. Both schools lasted two weeks and included a broad program of lectures, hands-on classes in regional forecasting and climate applications modeling, and a variety of field measurement activities with associated student projects that were presented at the culmination of each school.

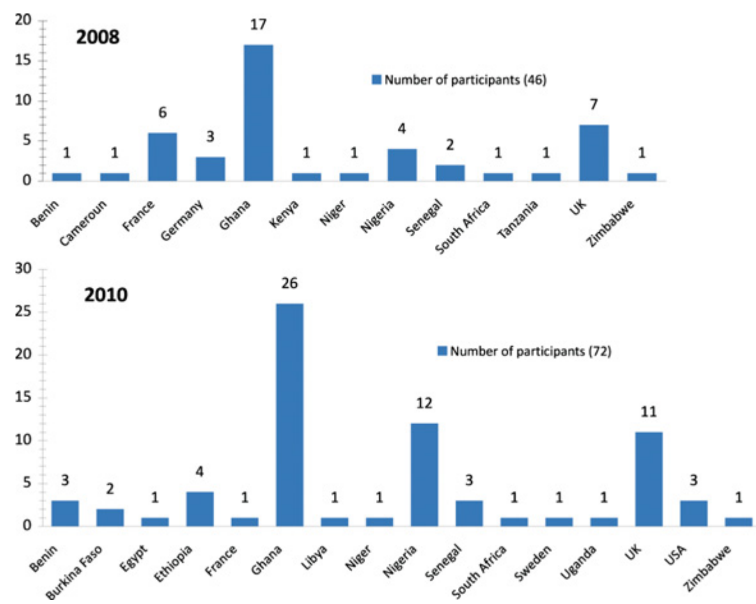


FIG. 1. Distribution of students by country of study/origin in the 2008 and 2010 summer schools.

From its inception, the summer school program was designed around the concept of integrating undergraduate and new Ph.D. students from all over the globe with research interests in African meteorology and climate. Figure 1 documents the country of study/origin of the students who participated in each school. The attendance of African students from across the continent was funded under the budget of each school, with about half originating

AFFILIATIONS: TOMPKINS—Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy; PARKER, HOBBY, KNIPPERTZ, AND NICKLIN—School of Earth and Environment, University of Leeds, Leeds, United Kingdom; DANOUR AND AMEKUDZI—Department of Physics, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana; BAIN—Met Office, Exeter, United Kingdom; DOMINGUEZ AND LAMB—Cooperative Institute for Mesoscale Meteorological Studies, and School of Meteorology, University of Oklahoma, Norman, Oklahoma; DOUGLAS—National Severe Storms Laboratory, National Oceanic and Atmospheric Administration, Norman, Oklahoma; FINK—Institute of Geophysics and Meteorology, University of Cologne, Cologne, Germany; GRIMES [deceased]—Department of Meteorology, University of Reading, Reading, United Kingdom; YORKE—Ghana Meteorological Agency (GMet), Accra, Ghana
CORRESPONDING AUTHOR: Adrian Tompkins, Earth System Physics, ICTP, strada costiera 11, 34151 Trieste, Italy
E-mail: Tompkins@ictp.it

DOI:10.1175/BAMS-D-11-00098.1

CROP-MODELING CLASSES

Students were introduced to the practical aspects of impacts modeling through an introductory lecture accompanied by two computer classes using a dynamical crop model called "GLAM." The model's relative simplicity makes it well suited to this kind of activity. First, a lecture outlined the processes simulated by GLAM, the input data requirements, model output, and the calibration procedure. During the computer classes, the students learned how to calibrate and run the model to simulate historic groundnut yields for a 1° x 1° latitude–longitude grid cell in Ghana (Fig. 2). A series of tasks—including changing the input data, method of calibration, and planting routine—helped the students gain a greater understanding of the modeling procedure. The students also acquired experience in using the Linux operating system and in comparing the skill of the simulations using basic statistics such as root-mean-square error and correlation. Future impacts-modeling classes could further complement the lecture content by demonstrating the use of seasonal or longer-term climate forecasts.

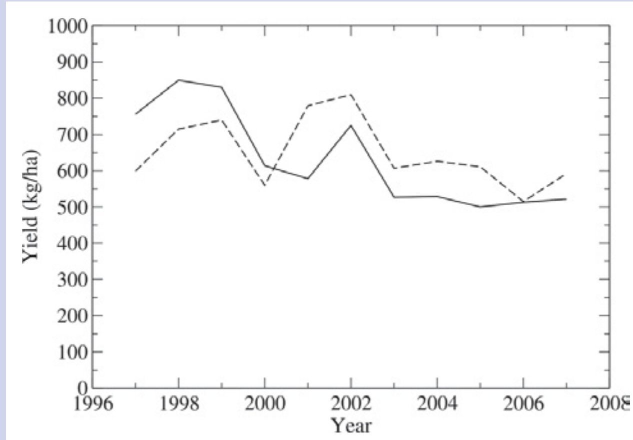


Fig. 2. Observed (solid) and simulated (dashed) groundnut yield for a 1° latitude by 1° longitude grid cell centered on 8.5°N,0.5°W in Ghana, produced by the students in the laboratory class. The students investigated the effects of changing planting dates, altering rainfall onsets and break cycles, and increasing/decreasing daily mean temperature.

from within Ghana. European students were mostly from France, Germany, and the United Kingdom, due to the involvement of lecturers from these countries in the school, in addition to a limited number of students from other European countries and North America. A table of the lecturers with their institutions and the years they contributed to the summer schools is in the electronic supplement to this article (http://dx.doi.org/10.1175/BAMS-D-11-00098.2). This broad engagement produced an environment in which African, European, and American students could not only have access to leading scientists in the field, but also could interact with their peers to form lasting working relationships. These links will serve well in the present highly competitive funding environment, in which an increasing proportion of European Union and North American research support is directed toward multicontinent cooperative actions. The multinational integration of the students and the wide range of activities gave the schools a unique and exciting atmosphere that we wish to maintain and foster in future similar projects here and elsewhere. In this paper, we report on the salient features of the summer school and its future prospects.

SCHOOL ACTIVITIES. School activities were multifaceted in both years. The foundation consisted of a series of lectures suitable for final-year undergraduate and beginning graduate (especially Ph.D.) students. The 2008 school concentrated initially on the fundamental components of West African meteorology and climate, with a broadening of the scope in the second week to include climate applications such as climate–health interactions. The 2010 school expanded this syllabus to add hydrology and agricultural modeling to the applications component, and covered seasonal climate forecasting issues in addition to short-range weather time scales. In both events, groups of three students were provided with a hands-on opportunity to make daily weather forecasts for the region. To inspire competition and motivation, points were awarded for forecast accuracy in a "weather game" over the duration of the schools.

There is a learning curve in exporting to Africa the teaching practices that work well in Europe and the United States. The experience of the first school demonstrated that slow (or nonexistent) Internet connections and disruptions to the local electrical power supply were facts of life that significantly impeded the learning process. In the second school, these problems were overcome by the following actions: use of Linux as a more efficient operating system; ensuring generators were available to replace grid power; designing scripts to download weather model output files overnight; and reducing reliance on Internet accessibility. The support of local technical staff was vital in providing quick fixes to unexpected problems so as to maintain the smooth running of practical sessions.

Afternoon laboratory classes included lessons in agricultural modeling (see Sidebar 1) and time allocated for work on student projects related to the field work. The field work was a unique part of both schools, providing students with the opportunity to have hands-on experience with a wide range of instrumentation (see Sidebar 2).

SUCCESSES, CHALLENGES, AND FUTURE OF THE SUMMER SCHOOL. *Successes.* One of the major successes of each school was that for the majority of participants it was a unique event in their careers. For African students, it was their first taste of an international meeting with the opportunity to initiate professional acquaintances with peers from many countries that can be built into long-term collaborations. For the students from Europe and the United States, it was their introduction to the African environment and an initial opportunity to meet many African peers. The formal level of European engagement was heightened in both schools for the third-year undergraduate participants from the University of Leeds (environmental science and meteorology majors), who subsequently were awarded degree credit for an optional module titled "Meteorology and Climate of Africa: Summer School." To receive this credit, the Leeds students were required to undertake preliminary (preschool) exercises and, after returning to their home campus, produce additional practical reports based on their in-school fieldwork. There is considerable potential for the growth of awarding formal degree credit for participation in future schools, including by African universities.

The field measurement efforts were considered a great success of both schools. They were facilitated substantially by a combination of instrument contributions from Europe and North America with the ease of access to and use of the permanent field sites operated by KNUST. These endeavors provided surface and (to a lesser extent) upper-air data that were accessible for lectures and student projects at a high temporal resolution, for a region for which such data are very rare. Examples appear in Figs. 3 and 4. These highly informative measurements will continue to inspire both the lecturers and students and bring them together to investigate synoptic features of this understudied region. The first example of this inspiration, including use of Kumasi data, appears in a recently published paper on the summer stratus cloud over southern West Africa. This effort involved "north–south" collaboration and coauthorship between the University of Leeds, Ghana Meteorological Agency (GMet), and the University of Cologne, among other institutions.

Both the African and non-African students benefited from lecturing teams that possessed substantial and wide-ranging experience. Many of the lecturers had pioneered investigation of the globally unique aspects of West African weather systems, the resulting regional monsoon climate, and their relations with the larger climate system. All lecturers continue to be actively engaged in the scientific and societal challenges that result from this region experiencing the largest climate change on the planet during the last 60-plus years. The importance of this work is heightened by considerable uncertainty concerning the response of the West African monsoon system to ongoing global warming.

However, developing the opportunity to conduct the two summer schools held to date involved overcoming a number of challenges. Continuing the schools into the future will require similar persistence. We turn now to those challenges.

Logistics. Organizing a school program of this nature is a significant task, since it requires the availability and use of multiple accommodation options, lecture theaters, several field sites, meal choices, and computer laboratories. Fortunately, the KNUST campus was able to provide all of the necessary facilities and services for both schools. The significant distances between some of the venues required considerable transport coordination for more than 50 students and staff during a packed schedule, and therefore was a significant logistical challenge. Contingency plans for unforeseen circumstances—such as power and Internet outages and student health and safety—increased the preparation requirements.

Running a summer school is a learning process and always can be improved. To this end, both schools conducted student surveys and held debriefing meetings with the lecturers to assess which aspects had gone well and which elements could be improved for future schools. In general, both schools were well received by the students, and logistical problems that arose in the first school, such as with accommodation standards and inadequate facilities in the computer laboratories, were addressed satisfactorily in the second school.

Lecture content. A major challenge was setting the appropriate lecture content level for students with a wide range of backgrounds. The academic/scientific levels of the participants extended from the latter stages of undergraduate programs, to graduate students embarking on research careers, to (in a few cases) individuals with significant early-career research experience in closely related environmental sciences. Achieving the desired equilibrium learning level was pursued using several approaches. At one extreme and as described previously, some of the advanced undergraduates were assigned additional pre- and postschool activities for degree credit. At the other extreme, individual lecturers had one-on-one contact with early-career scientists from related disciplines to help bridge the disciplinary gaps. In between those extremes, graduate students also benefited from that type of engagement with lecturers concerning their developing thesis/dissertation topics.

The significant number (10–14) of lecturers present at each school led to challenges in coordinating the lecture program to achieve a smooth development of material without gaps or overlaps. This possibly resulted in some lecturers being underutilized. Also, since the second school extended the scope of the lecture material, it was found that some students were partially lacking the basics. Therefore, short (10-minute) briefing-style talks were inserted into each daily forecast laboratory class to introduce and develop a basic concept, such as potential temperature.

One suggested approach to addressing the above challenges is to extend the length of the program and make associated adjustments to its structure. The adjustments could include lecturers coming in shifts and possibly also separating the students into groups. The latter approach would require an additional preschool period for undergraduates that would cover basic lecture material. This would, of course, come at both financial and organizational expense and would require an even greater time commitment for the school organizers, both local and external. An alternative approach would be to take advantage of the significant lecturing team to divide students into more stratified and focused groups in parallel sessions, if sufficient facilities were available. Another option would be to target the summer school only at beginning graduate-level students. As research programs in the climate sciences grow in the region, more local students will be available to make this viable. This would be at the expense, naturally, of losing the potentially significant number of undergraduate students from Europe and North America that may take the school as an accredited course component, and whose involvement likely enriches the experience for the African students. All of these options remain under consideration for the next school, which likely will occur in 2013.

Local expertise and field equipment. A minority of the lecturers at the first two schools were from African universities and institutes. The school organizers feel there is a real need and potential to improve this ratio in the future, while retaining a mix of experts from across the globe to facilitate the exchange of ideas and methods. While the growth of local expertise in all the fields required will take time, there was a tendency to underutilize the existing African scientific expertise—even from within Ghana—which possibly was due to a lack of confidence. One way to improve this situation would be to develop and draw on a database of regional experts according to their field.

As previously indicated, the field measurement efforts were considered a great success of both schools. While they relied to a certain degree on the support of European and North American institutions to ship in instrumentation at considerable cost, the access to the KNUST permanent field sites will ensure that a core field program is possible in future schools at that institution, even without such a high level of external support. With the continuing commitment of GMet, an upper-air observing component will be sustainable along with vital surface observations. Forming a regional rather than local steering committee for the school program could also strengthen the possibility of securing funding to enhance the instrumentation network.

Location of future schools. Kumasi was chosen for the first two summer schools due to the recent establishment of a regional meteorological program at KNUST and the availability there of all necessary facilities. However, that location requires a minimum of four hours ground transport from the international airport at Accra, which increases the costs and logistics involved. This separation also

FIELD WORK

Field work was a central part of each school, and provided many of the students with their first opportunity to make meteorological measurements. Each school made significant use of the meteorological ground stations on the Kwame Nkrumah University of Science and Technology (KNUST) campus, located in Kumasi, which included rain gauges, anemometer systems, and dry- and wet-bulb thermometers in Stevenson screens. These routine KNUST measurements were supplemented in the two schools with mobile surface weather and energy flux stations from the University of Leeds and the University of Reading, respectively, and by a permanent donation of automatic, high-resolution rain gauges and a fully equipped automatic weather station from the University of Cologne.

The generous support of both schools by NOAA and the Ghana Meteorological Agency (known as GMET) meant upper-air observations were also possible, with students gaining experience in launching and tracking both pilot balloons (PIBALs) and radiosondes. A sequence of radiosonde soundings made during an all-night observing session (Fig. 3) clearly shows the distinct southwesterly monsoon layer, the tropical easterly jet and tropopause, and various other features that are common to all of the soundings. Both schools included an overnight session of upper-air measurements, using candle illumination to permit balloon tracking, in an attempt to record the evolution of the nocturnal boundary layer. This exercise had only mixed success, both in terms of the clear skies needed for PIBAL observations and the enthusiasm of the students for manning the 2 a.m. "graveyard" shift!

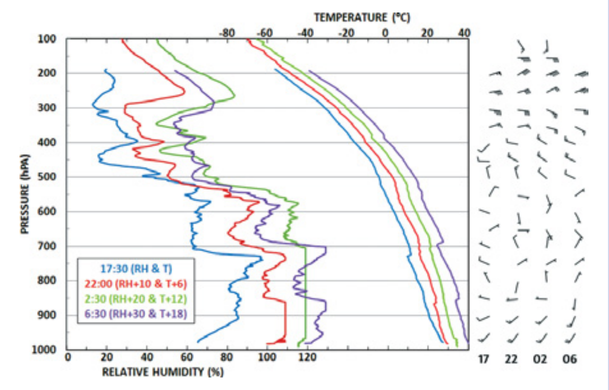


Fig. 3. Temperature (*T*), relative humidity (RH), and wind profiles as measured by four sequential radiosonde launches at the KNUST field site during the night of 23 Jul 2010 (times are local, with each successive *T* and RH profile offset by 6 K and 10%, respectively, for clarity). The wind plotting is conventional, with a full barb for 5 m s^{-1}. The *T* and RH plots reveal the time continuity of subtle stable layers and their associated RH changes over the 12-h period; the wind plots show that these wind shifts are associated with vertical shear. Saturated cloud layers (vertical parts of RH profiles below 700 hPA) are evident in three profiles. Common to all of the wind profiles is the southwesterly monsoonal flow from the surface to about 900 hPA, the strong tropical easterly jet near 200 hPA that is above a westerly wind layer from 500–400 hPA, and subtle variations in the meridional flow in the middle troposphere.

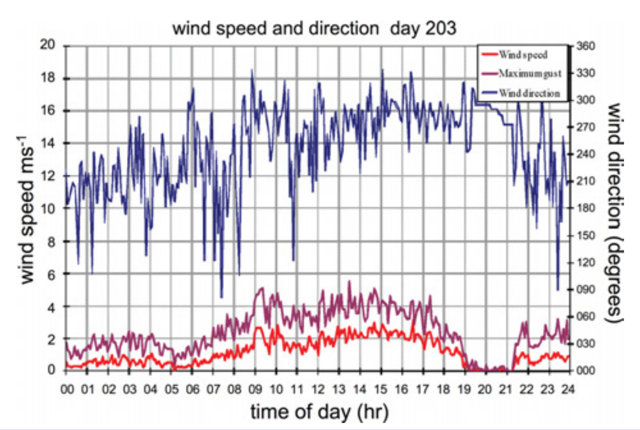


Fig. 4. Surface wind recordings at the KNUST field site during 22 Jul 2010. The very light surface wind strength associated with daytime boundary layer mixing remarkably drops to zero shortly after sunset (around 1900 LT). Around 2100 LT, the wind picks up again as the nocturnal jet strengthens and mixes down toward the surface.

The combination and variety of the available instruments meant that a wide range of phenomena could be studied by the students. For example, the portable weather mast provided by the University of Reading was operated at the KNUST field site to provide five-minute averages of various weather parameters during the entire two-week period. It yielded some beautiful examples of the development of nighttime surface winds associated with the overlying nocturnal jet (Fig. 4), which will be a valuable teaching resource in the future. Students conducted projects examining the temporal variability of rainfall, the boundary layer diurnal cycle, and the surface energy budget, and related their findings to knowledge of West African meteorology and the monsoon boundary layer gained in the lectures and forecast classes.

means that an individual's time commitment to the program is lengthened by two additional days, due to the transfer between Accra–Kumasi–Accra. Also, poor and expensive air transport links between French-speaking African countries and Ghana were an impediment to increasing the involvement in the first two schools of lecturers and students from the nonneighboring French-speaking African countries. However, despite these linguistic and logistical difficulties, the organizers consider it worthwhile to further pursue the development of a more truly pan-West African event.

Holding the summer school at KNUST every two or three years has several advantages. For example, the school can evolve and improve with time as the local organizers learn from previous experience, it will continue to have access to good facilities, and there will be an increasing number of local undergraduate and graduate students who can benefit from the program. On the other hand, rotating the location either within Ghana or possibly within West Africa would give the school wider African ownership, could reach a greater pool of students, and may encourage the involvement of more local and nonlocal organizers. If future schools were to remain in Ghana, for example, they could rotate between KNUST, the University of Cape Coast (at which a climate science program is being established), and possibly the University of Ghana campus in Legon near Accra. Both of the latter two universities also have excellent facilities for hosting such an event.

The school funding environment. The first school was funded by a British Council/Department for Education and Skills (DfES) grant and was organized by the University of Leeds in that country, while the second school was funded by the Italian Ministry of Education (MUIR) and administered by the Abdus Salam International Center for Theoretical Physics (ICTP) in Italy. This external funding paid for the local costs of the school, such as ground transport and rental of lecture room facilities, and for financing the attendance of African students. All non-African students and all lecturers were funded by their home institutes or governments, including the costs of shipping equipment used in the program.

The summer school could continue as a biennial or triennial event, with the necessary funding being solicited on a school-by-school basis. Many institutes worldwide include development and training in their mandates, allocating or obtaining funds for regular on-site courses with support for developing country candidates. Examples include ICTP (which organized the second school), the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) at The University of Oklahoma, the International Research Institute for Climate and Society (IRI) at Columbia University, and the Institut de Recherche pour le Développement (IRD) of France. These and similar institutes could be encouraged to link up with the Ewiem Nimdie event, running training courses offsite and thus cosponsoring an individual school. It is possible that each sponsoring institute would prefer to place emphasis on its own areas of research, which could widen the scope of individual summer schools.

Clearly, the summer school would be more sustainable if additional regular funding sources were established. Considering the extensive media attention within Ghana that the first two schools received, and the climate-related scope of the school program, the organizers feel that there is great potential for gaining sponsorship of the school from national or multinational companies operating in the region.

OUTLOOK. The first two Ewiem Nimdie summer schools were considered successful exercises by all those involved. They gave African students access to leading international specialists in African weather and climate research. Non-African students benefited from the chance to experience African weather firsthand, and students of all nationalities had the opportunity to mix and form lasting working relationships. Much was learned by both the local and nonlocal organizers in terms of staging an event of such a complex nature.

The summer schools should grow in stature and could act as a global blueprint for other similar regional events in developing nations. Priorities for the near future should include building networks of African expertise from both French-speaking and English-speaking African countries, as well as securing regular funding for the school from a wider spectrum of national and international organizations. If the school continues to include a strong emphasis on the advanced undergraduate level, efforts could be made to have the event accredited as a module in university programs both within and outside Africa, following the example set by the University of Leeds. This status would enhance the recruitment of participants. The possibility of rotating the location of the school within Ghana or between French-speaking and English-speaking West African countries also should be considered.

Above all, the Ewiem Nimdie Summer School Series involves helping Africa help itself. Therefore, institutes or individuals interested in contributing to future events should contact the corresponding author of this article.

ACKNOWLEDGMENTS. This article is dedicated to the memory of the late David Grimes, our dear friend, colleague, and co-author, who contributed so much to the understanding of precipitation in Africa and to educational outreach. The two summer schools were funded by grants from the United Kingdom's British Council/Department for Education and Skills and the Italian Government's Ministry of Education (grant award ICTP:241.FITU.11.G), respectively. The Kwame Nkrumah University of Science and Technology allowed the use of many university facilities at each school free of charge and acknowledges the efforts made by its local support team. The following institutes generously provided equipment and associated shipping costs: University of Cologne (Germany), NOAA National Severe Storms Laboratory (USA), GMet, and the Universities of Leeds and Reading (UK). Each school was supported by a large number of European and North American lecturers, who spent time to prepare teaching material and find travel funds; they are listed in the electronic supplement to this article (http://dx.doi.org/10.1175/BAMS-D-11-00098.2).

FOR FURTHER READING

Challinor A. J., T. R. Wheeler, P. Q. Craufurd, J. M. Slingo, and D. I. F. Grimes, 2004: Design and optimisation of a large-area process-based model for annual crops. *Agric. For. Meteorol.*, **124**, 99–120.

TECHNOLOGY

SMOS Satellite Improving Hurricane Forecasts

The amount of water in the soil and salinity in the oceans are both key variables linked to Earth's water cycle, affecting weather and climate. The European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) satellite was designed to measure what it was named after, but it turns out it can do more. SMOS is proving it can also offer insight that could aid in improving hurricane forecasts.

The SMOS uses a microwave radiometer to measure Earth's brightness temperature, which corresponds to surface emissions of radiation. The sensor works in the "L-band" at frequencies that also can be used to track surface wind speeds over oceans, even in cloudy and rainy conditions. Because gale-force winds affect the microwave radiation emitted from the ocean surface, changes can be linked directly to the strength of the wind. The radiation detected by the satellite is also less disturbed by rain and atmospheric effects than higher microwave frequencies, making SMOS uniquely equipped for extreme conditions, such as those in a hurricane.

The researchers discovered this capability when analyzing

FREEZEPRUF YOUR GARDEN

Good news for gardeners in harsher climates. A new topical spray has been developed that is designed to protect foliage, flowers, and fruit from cold temperatures—an "antifreeze" for plants. According to researchers at The University of Alabama and Miami University of Ohio, who developed the spray, using FreezePruf is the equivalent of moving plants south about 200 miles. Tests revealed that the all-natural spray decreased plants' first damage temperature and mortality temperatures by 2° to 9°F, depending on the variety, improving their natural ability to tolerate freezing conditions. "We noted beneficial effects within hours of application," says David Francko, professor of biology at the University of Alabama. "Our results suggested that the spray formulation could add the equivalent of approximately 0.25 to almost 1.0 USDA Plant Hardiness Zone to the cold hardiness rating of the plants used in the experiments." The researchers note that the spray is not only friendly to plants, but the environment as well. It's made from a combination of cryoprotectants and other ingredients, all of which are biodegradable. FreezePruf is available online at freezeproof.com. (Source: American Society for Horticultural Science)

SMOS data from Hurricane Igor in the North Atlantic in 2010. They are hoping it will be useful in determining the intensity of developing hurricanes in the eastern tropical Atlantic and tropical cyclones in the middle of the Pacific, both of which are difficult to reach by plane.

SMOS has also found that salinity in the surface waters changes in the wake of a hurricane, the first time this has been detected from space. When combined with both sea surface temperature and height information, the SMOS salinity data will aid in monitoring fresh and warm-water interactions near tropical cyclones and how they relate to storm intensity. (Source: European Space Agency)

ON THE WEB

Weather on Steroids

The strange weather patterns this winter raised the usual questions on the link between climate change and extreme weather, and many more tried to unearth why our weather seems out of whack. With different answers in different places, a clear-cut explanation can be difficult to find. To help address this problem, researchers at the University Corporation for Atmospheric Research (UCAR) have created a new website called "Weather on Steroids."

"This is a very complicated subject," explaining the climate–weather link, comments David Hosansky, spokesman for UCAR, which produced the report and also operates NCAR in Boulder, Colorado. "We wanted to reach out to the public and present it in a way that could resonate widely."

On the site, the scientists draw from the latest research to answer questions about possible links between extreme weather and Earth's warming climate. A few of the many features include "Doping the Atmosphere," "Extreme Weather Forensics," and "Steroids, Baseball, and Climate Change," which explains what home runs and weather extremes have in common.

"We wanted to give a clear view of the science to decision makers, the media, and members of the public," Hosansky says, "and show where the science is and where the science is going."

For more, visit the website at https://www2.ucar.edu/atmos-news/attribution. (Source: ABC News)

ECHOES

"As a weather watcher, I feel like the weather is officially broken."

—Mike Weilbacher, executive director of the Schuylkill Center in Philadelphia, Pennsylvania, which promotes the preservation of the natural environment through environmental education. The season of strange winter weather affected the wildlife in the center, with beehives unusually active, baby pigeons born early, and turtles not hibernating as they should be. Weilbacher said the season was setting records for the number of different weather records achieved and noted the importance of looking at long-term trends for answers on the see-sawing weather. (Source: CBSPhilly)

Online Tool Pinpoints U.S. Emissions

Want to find out what kind of toxic substances may be floating in the air of your community? The Environmental Protection Agency (EPA) has made it as easy as plugging in your ZIP code. The Greenhouse Gas Emission Data tool shows users the amount of greenhouse-gas emissions along with where they originate in a particular area.

"Carbon pollution is pretty abstract for most people, and they don't [know] where it comes from and who's responsible," says David Doniger, policy director for the Climate and Clean Air program at the Natural Resources Defense Council. "These kinds of right-to-know tools are very popular and can make a difference. Once people know the level of greenhouse gases in their backyards, they will demand to know what company officials and elected officials will do about it."

The tool is modeled on the EPA's 20-year-old toxins release inventory map and is based on 2010 data collected from more than 6,700 facilities across nine major industries. Gina McCarthy, assistant administrator for EPA's Office of Air and Radiation, notes that the database is not a regulatory device but can be useful for decision making among companies, nonprofits, and communities working to reduce greenhouse gas emissions.

The database lets users find facilities by industry, state, and community, and rank them by their greenhouse-gas emission levels. It allows utilities to track their own emissions across plants and environmentalists to narrow down the biggest emitters. Individuals can use the database to find the level of greenhouse-gas emissions from the power plants, refineries, and cement plants in their communities.

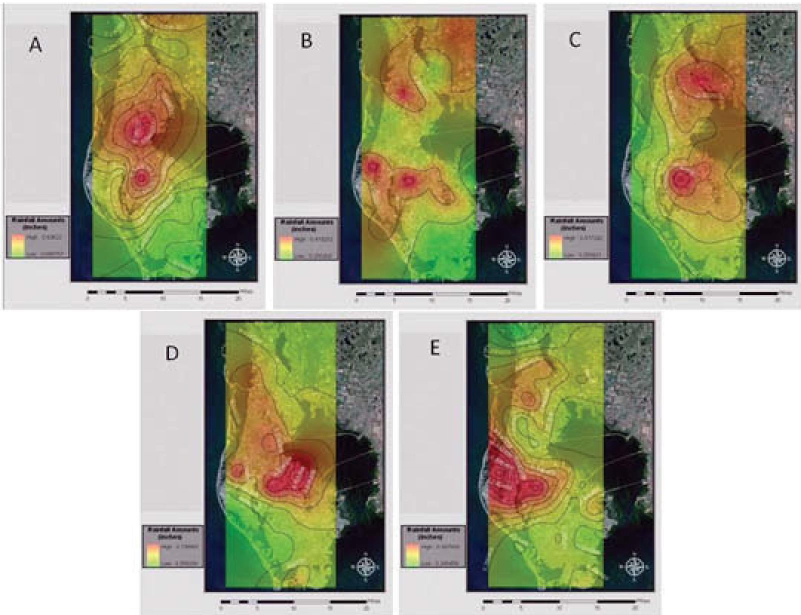
Check out the tool at http://epa.gov/climatechange/emissions/ghgdata. (Source: *Los Angeles Times*)

CHAPTER CHANNEL

Rainfall and Severe Weather Influences in Pinellas County, Florida

In January, Cristina Mazza Schoonard of the Department of Geography, Environment, and Planning at the University of South Florida spoke to the West Central Florida chapter about her research, "The Influence of Meteorological Parameters on Rainfall and Severe Weather in Pinellas County, Florida." She began with the objectives of her research, the first being to identify the dominant surface wind directions in coastal Pinellas County for June, July, and August from 1995 through 2009 using the 1200 UTC sounding data from Ruskin, Florida. Ruskin is south of Tampa and is where the NWS forecast office for Tampa Bay is located; Pinellas County, which includes the cities of St. Petersburg and Clearwater, is across Tampa Bay to the west of Tampa. She found that in Pinellas County, an easterly wind flow dominated the area, but the south and west wind flow days brought the most rain to the Pinellas peninsula. She noted that this information can be useful especially for aviation and boating forecasts.

Schoonard went on to discuss her second objective, which was to determine the spatial distribution, timing, and amounts of rainfall in Pinellas County associated with the dominant wind regimes. She found that westerly winds were associated with the greatest chances for sum-



Rainfall composites for Pinellas County, Florida, with the following surface wind directions: A) 1°–60°; B) 61°–120°; C) 121°–180°; D) 181°–240°; E) 241°–300°.

mer rain in Pinellas County. She noted that a further examination of rainfall shapefiles in ArcGIS revealed that in all wind-direction categories except for the 241°–300° wind direction, the largest amounts of rainfall occur in two maxima within the center of the Pinellas peninsula.

Furthermore, she highlighted some work she had completed examining Nexrad Level II radar files in Gr2Analyst. She revealed that rain can be expected earlier in the day when winds are out of the west, compared to days when rain is associated with an easterly flow of air. She reported that this supports previous research by Gentry and Moore (1954). Schoonard highlighted the usefulness of this information for local short-term forecasts by providing generalizations that can be made of what to expect for each wind category. For example, on a day with a wind direction in the 181°–240° category, it appears likely that rain will occur in the eastern center of the peninsula over the St. Petersburg-Clearwater International Airport. Precipitation on southwesterly wind flow days is also more likely to occur much earlier in the day than on days dominated by easterly wind flow. This information is especially beneficial because of the possible impact on airport operations.

The third objective of Schoonard's research was to determine the correlations between atmospheric parameters and precipitation amounts during June, July, and August from 1995 to 2009. She found that wind speed is positively and statistically significantly correlated with precipitation in two wind direction categories (121°–180° and 181°–240°). Precipitable water is positively and statistically significantly correlated with precipitation in almost every wind direction category. This information about precipitable water and wind speeds is helpful when making short-term forecasts as well. For example, Schoonard explained, on a day with a southerly wind direction between 121°–240°, higher wind speeds could bring more precipitation. A day with higher precipitable water most likely means that more precipitation will fall.

Schoonard then discussed her fourth objective, which was to examine the effect of wind flows on severe weather events in Pinellas County. She found that most severe weather occurs on days with a southeasterly wind flow (61°–180°). Hail was associated with a southeast wind regime; tornadoes with an east and southeast flow; strong wind with an east, southeast, and southerly flow; and floods with a flow from the southeast and southwest. She again highlighted the usefulness of this information to forecasters by providing case studies of severe weather and providing additional support to the severe weather alert decision-making processes.

Schoonard wrapped up by discussing the fifth and final objective of her research, which was to determine which atmospheric parameters and indices were associated with severe weather events. She noted that days with hail had the lowest average wind speed, a moderate average convective available potential energy (CAPE) value, and the lowest precipitable water average of the severe events studied. Days with tornadoes had moderate to higher average wind speed, a higher precipitable water value, a higher severe weather threat index (SWEAT) value, and the lowest average CAPE value of the severe events studied. Strong wind events had moderate values for all variables. Of the severe weather events considered in her study, flooding had the highest average values of wind speed (2.8 m s^{-1}), CAPE (1437 J kg^{-1}), precipitable water (51 mm), and SWEAT (198). From her study, more information is revealed about what values of certain atmospheric parameters and indices are more often associated with different forms of severe weather. For example, on a day with high wind speed, CAPE, precipitable water, and SWEAT, forecasters might issue flood warnings for Pinellas County.

—David R. Roache
West Central Florida chapter.

PAPERS OF NOTE

Temperature Sensitivity to Climate Forcing over a Half-Million Years

The global temperature response to changes in the radiative forcing of Earth's climate, known as climate sensitivity, can be evaluated from records of natural climate variability in the recent geological past, which was dominated by large "ice-age" swings of global climate. For this purpose, we made a global compilation of sea surface temperature (SST) records that span one to five ice-age cycles and combined these with ice-core temperature reconstructions to determine the sensitivity of Earth's climate to long-term climate forcing.

Our dataset portrays the temperature response to radiative forcing changes over a relatively long period (up to 500,000 years) that was characterized by several pronounced climate cycles. We consider the response both in a global mean sense and in separate 10° latitude bands. A strong Equator-to-pole gradient in temperature sensitivity to radiative forcing is found in both scenarios, but especially in the latitude-separated case. From the combined data, we derive an estimate of global climate sensitivity over the last half-million years with a mean value between 0.85 and 1.05 °C/W m^{-2}, depending on the treatment of aerosol effects. Uncertainties about the mean are estimated at –0.4/+0.5 °C/W m^{-2}, and the mean is close to previous estimates.

The latitude-separated assessment reveals distinct north–south differences in the temperature response to radiative forcing, with strong indications of "tropical dampening" and "subtropical amplification" of that response, relative to the mean. We also determined a normalized polar amplification, which is the temperature response per W m^{-2} of radiative change in polar regions relative to the global mean. This ratio was found to be 0.9 (–0.2/+0.6) and 1.4 (–0.4/+1.1) for Greenland and Antarctica, respectively.

These values indicate that the large temperature changes that have occurred in the Arctic and Greenland can be entirely ascribed to the large radiative impacts in that region from the ice-albedo effect associated with the waxing and waning of large continental ice sheets in the Northern Hemisphere. In the Antarctic, the response to radiative forcing was considerably stronger than the global mean, and a simple scale analysis shows that this was a likely consequence of large glacial-interglacial changes in the Antarctic sea-ice extent.—Eelco J. Rohling (University of Southampton), M. Medina-Elizalde, J. G. Shepherd, M. Siddall, J. D. Stanford. *"Sea Surface and High-Latitude Temperature Sensitivity* *to Radiative Forcing of Climate over Several Glacial Cycles," in the 1 March* Journal of Climate.

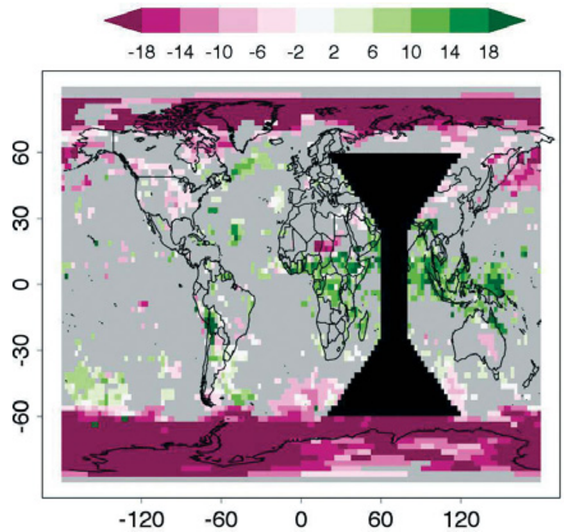
Observed Increases in Global Solar Radiation and Precipitation Variability

Weather-dependent processes such as disease outbreaks, the photosynthesis carried out by forests and crops, and the amount of runoff from rain events are sensitive to the variability as well as the mean state of climate parameters. For example, with photosynthesis, the effects of a positive solar radiation anomaly do not exactly counterbalance the effects of a negative solar radiation anomaly. Any changes in day-to-day variability will thus have a net effect. Satellite data have now been used to show that the day-to-day variability of two such climate parameters—solar radiation and precipitation—have been increasing in recent years.

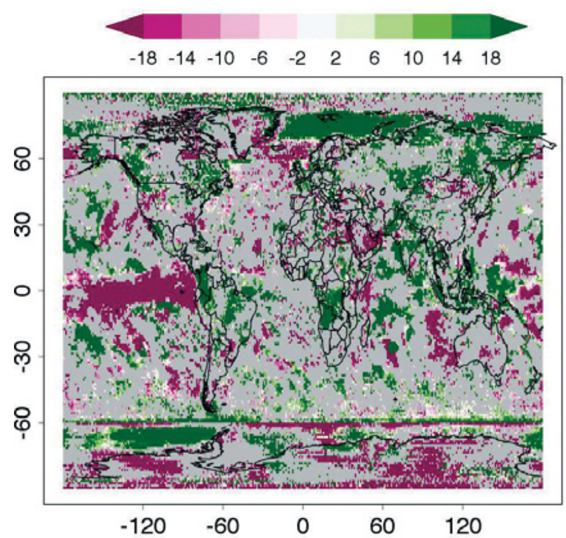
We examined day-to-day variability in surface-level solar radiation across the globe between 1984 and 2007 using data from the International Satellite and Cloud Climatology Project. We found significant changes in this variability over 35% of the globe, including large increases over tropical land areas throughout the year and also increases over northeastern North America during December–January–February. Changes in precipitation variability were estimated using data from the Global Precipitation Climatology Project from 1997 to 2007 and were found to be significant over 40% of the globe. As with solar radiation, large increases in precipitation variability were found over tropical land areas. Furthermore, we determined significant correlations between these changes in variability and cloud properties, with larger levels of variability being associated with greater amounts of deep convective clouds.

These increases in the day-to-day variability of solar radiation are expected to reduce photosynthesis, and thus reduce the potential of terrestrial ecosystems to sequester CO_2 from the atmosphere. The largest effects may be in the tropical rainforests, which currently store vast amounts of carbon in their biomass. Agriculture in the Tropics may also be affected, with implications for both food and biofuel.

To improve understanding of these issues, additional work needs to be done that focuses on the still-uncertain physical mechanisms that ultimately control the degree of day-to-day variability. While climate models can be used to understand current and potential future changes, this is challenging because high-frequency variances are seldom reported in model output and thus are rarely validated. In addition, the higher-order statistics of solar radiation and precipitation are likely to be sensitive to some of the most uncertain model parameterizations, including those for clouds.—David Medvigy (Princeton University) and C. Beaulieu. *"Trends in Daily Solar Radiation and Precipitation Coefficients of Variation since 1984," in the 15 February* Journal of Climate.



Changes in solar radiation variability. **Percentage changes in the annual coefficient of variation of solar radiation between 1984 and 2007. Grid cells without a statistically significant change are shown in gray, and the Indian Ocean sector is blacked out because data were not available for much of this period.**

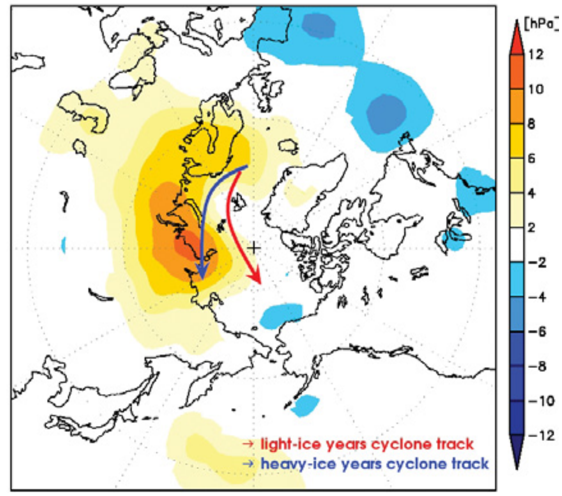


Changes in precipitation variability. **Percentage changes in the annual coefficient of variation of precipitation between 1997 and 2007. Grid cells without a statistically significant change are shown in gray.**

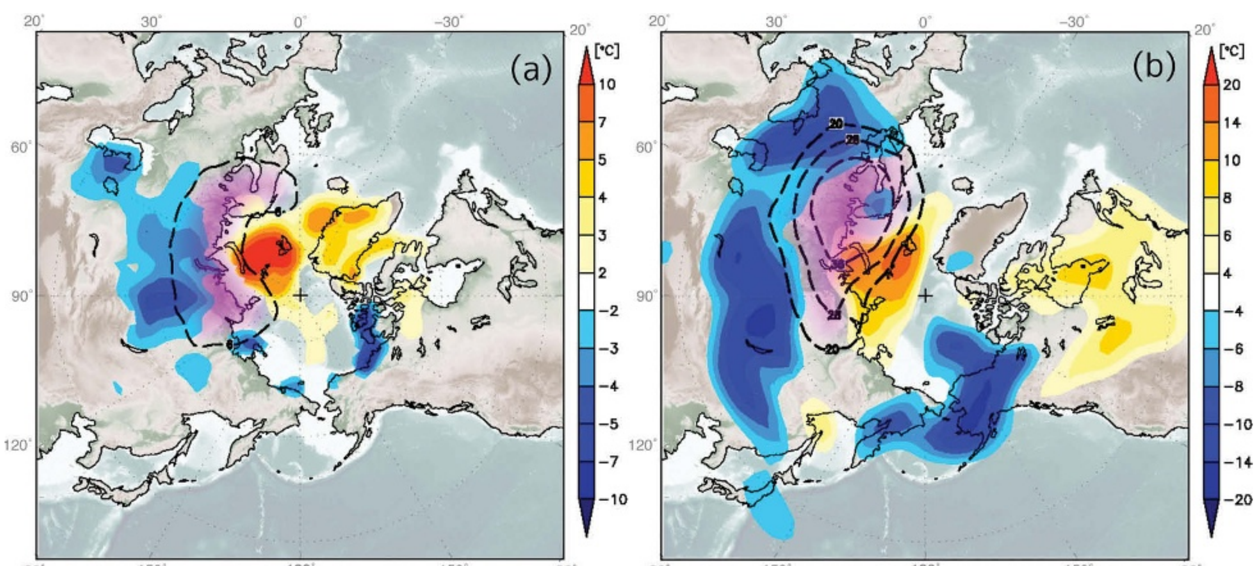
Sea Ice Variability in the Barents Sea Brings Arctic Warmth, Continental Cold

The coldness of Japanese winters is generally explained by the combined effects of climate variations, including El Niño–Southern Oscillation (ENSO) at low latitudes, and the positive/negative phase of the Arctic Oscillation (AO) at high latitudes. Occurrences of severe cold such as during the 2011–12 winter, however, cannot simply be explained by such a coupled effect, and thus are often difficult to predict. At larger spatial scales, warm Arctic and cold Siberia conditions are often observed in pairs, and a linkage to global warming has been receiving increasing attention. Our research looked into this link and determined that winter cyclones originating in the Barents Sea north of Russia tend to take northward paths under recently reduced sea ice, compared to those years with heavy ice. The northward shift in cyclone paths brings anomalous warm air over the Arctic Ocean, while over Siberia, a cold air mass is apt to move in from the north. This phenomenon may help explain recent cold events in Japan despite ongoing global warming.

The findings were obtained from atmospheric reanalysis data from 1979 to 2011. In our study, we focused on the wintertime cyclonic activity in the Barents Sea, where the Arctic warming is the most evident, and investigated changes in cyclone tracks in response to sea ice variability, as well as their effects on the Arctic warming and Siberian cold. We found that under the reduced sea ice extent in the Barents Sea in winter, cyclone tracks tend to shift from the Siberian coast northward toward the Arctic Ocean. The resultant distribution of atmospheric sea level pressure facilitates warm advection over the Arctic Ocean; whereas over Siberia and the Norwegian coast, it creates conditions inducing cold anomalies. The cold air mass formed over



Shifting tracks. **Sea level pressure (hPa) anomaly and typical cyclone paths (Red arrow: light-ice years, Blue arrow: heavy-ice years). In the light-ice years, the Siberian High expands to the Arctic coast as the cyclone path shifts northward. The "+" on the map depicts the location of the geographic North Pole.**



Colder continents. **Surface air temperature (a) in relation to the WACS anomaly in the study, and (b) anomalous to the long-term mean during the week 26 to 29 Jan 2012. Areas enclosed by the dashed lines indicate anomalously high pressure (hPa). The "+" on each map depicts the location of the geographic North Pole.**

Siberia reaches downstream to East Asia and Japan within a few days, resulting in a colder winter in Japan.

Such warm Arctic and cold continental conditions are referred to as a warm-Arctic cold-Siberian (WACS) anomaly, and the WACS anomaly could be a procurer of severe weather in the downstream region. As in the winter of 2005–06, which brought heavy snow to Japan, the sea ice extent in the Barents Sea has been significantly low during the winter of 2011–12, which has resulted in the emergence of the WACS anomaly and cold and snow in Japan.

As the Arctic sea ice retreat is still robust, it is vital to utilize prediction models to investigate remote responses of atmospheric and oceanic circulation systems to the changes in sea-ice cover. Our findings of the WCAS anomaly suggest a close correlation between the warm Arctic conditions and climate variability at the downstream mid-latitudes.—Jun Inoue (Research Institute of Global Change, JAMSTEC), M. E. Hori, and K. Takaya. *"The Role of Barents Sea Ice on the Wintertime Cyclone Track and Emergence of a Warm-Arctic Cold-Siberian Anomaly," in the 15 March* Journal of Climate.

GEORGE VI MOVES THE LAKES

Imagine a lake that moves mysteriously as much as 5 feet a day. In Antarctica, researchers were surprised to find such a phenomenon occurring. While studying satellite images of the ice shelf lakes between 2001 and 2010, glaciologist Doug MacAyeal of the University of Chicago was startled by the appearance of these traveling bodies of water. The lakes sit above the George VI ice shelf (the same George portrayed in the movie *The King's Speech*), which extends westward from the long-arm Antarctic Peninsula that points toward South America. Although the researchers expected movement of the lakes, which appear each summer and refreeze in winter, it was the direction that took them off guard. Moving parallel to a coastline of the George VI ice shelf, it turns out the mechanism responsible is viscous buckling—a mechanism most familiar in TV ads showing the back-and-forth motion of pouring pancake syrup. The researchers explain that in the traveling lake case, the ice shelf is "pouring" horizontally and crashing into and oozing around nearby Alexander Island. As the ice crunches around the island, it moves the lakes along the coast instead of perpendicular to it. According to the researchers, the ice shelf has been thinning but remains healthier than some of other ice shelves nearby. "We're interested in surface lakes on ice shelves because they're the precursor of ice-shelf collapse," MacAyeal comments. "This ice shelf gives us longstanding lakes for reasons other than climate change, and with consequences that aren't going to kill the beast we're studying, so we can look at these lakes to see what's going on." That is, if the researchers can keep up with the speed the lakes travel. (Source: OurAmazingPlanet.com)

Stratospheric Sulfate Injections May Not Halt Climate Emergencies

Continued greenhouse gas emissions are projected to result in global average warming of 1.7° to 4.4°C this century, with roughly 2–3 times more warming in the high northern latitudes than the global average. Even under stabilized or zero emissions, the planet will continue to warm due to already emitted gases. This has prompted some to claim that the world is already committed to dangerous warming that could result in "climate catastrophes," such as the loss of polar bear habitat, displaced arctic ecosystems, thawing permafrost, rapid sea level rise due to melting Greenland and West Antarctic ice sheets, or a large reduction in crop production due to tropical warming. Injection of sulfate aerosols into the stratosphere to reflect incoming solar radiation has been proposed to counteract anthropogenic warming and, in particular, to avoid regional climate emergencies. Can climate changes in at-risk regions be avoided through the use of stratospheric aerosols? We simulate such a "geoengineered world" and find that while the avoidance of serious agricultural issues in the tropics may be possible, this strategy cannot eliminate the potential for polar climate emergencies.

Previous work using global climate computer models has shown that the climate changes under increased greenhouse gases are lessened with the introduction of stratospheric aerosols, but that the compensating effects are not perfect. We decided to investigate, in particular, whether the reason that would drive society to attempt geoengineering—the potential for so-called climate emergencies to occur—might be avoided.

We conducted a detailed analysis of the climate response to the joint forcing of increased CO_2 and stratospheric sulfate aerosols in a global climate model in three regions—the Arctic, West Antarctica and the Antarctic Peninsula, and the tropics. We also compared simulations that incorporate a full ocean general circulation model to simulations with a "slab" ocean, which prescribes the movement of heat in the ocean, to probe the uncertainties surrounding ocean dynamics.

Residual polar warming, the difference between warming under stratospheric aerosol injection and CO_2 warming without additional aerosol forcing, is still large (20%–50% of the changes in a warmed world) and cannot be compensated for without overcooling the tropics. This is partly due to the ineffectiveness of reflective sulfate particles in polar winter, but also largely due to atmospheric circulation anomalies that persist even with the aerosols. The resulting anomalous winds bring warmer and moister air to the polar regions and change the ocean circulation enough to pull warmer waters toward Antarctic shores.

The effectiveness of stratospheric aerosols is far from perfect, with the details of the regional climate response still highly uncertain and dependent on ocean dynamics. Our research highlights the need for a coordinated computer modeling effort, with an agreed-upon set of model configurations and geoengineering scenarios, to lend confidence to the outcomes expected from such a strategy. The Geoengineering Model Intercomparison Project (GeoMIP) aims to accomplish just that, with results appearing in the next Intergovernmental Panel on Climate Change assessment report.

While knowing the range of expected outcomes from such geoengineering efforts is necessary before any serious efforts at implementation are undertaken, there exist many more science and nonscience issues—such as just how much sulfate would be needed and whether the international community would cooperate, among others—that prohibit us from advocating for such measures at this time.—Kelly McCusker (University of Washington), D. S. Battisti, and C. M. Bitz, "*The Climate Response to Stratospheric Sulfate Injections and Implications for Addressing Climate Emergencies," in a forthcoming issue of the* Journal of Climate.

A Synoptic Perspective of the Record 1–2 May 2010 Mid-South Heavy Precipitation Event

BY JOSHUA D. DURKEE, LEE CAMPBELL, KYLE BERRY, DUSTIN JORDAN, GREGORY GOODRICH, REZAUL MAHMOOD, AND STUART FOSTER

During 1–2 May 2010, a series of strong thunderstorms led to 41, 57, and 43 tornado, severe wind, and severe hail reports, respectively, across portions of the southern United States. In addition to severe weather, these storms also distributed record-setting rainfall amounts across the mid-South region, which contributed to historic flooding across portions of central and western Kentucky and Tennessee (Fig. 1). This heavy precipitation event was sampled by multiple surface observational networks, including (but not limited to) 48 research-grade automated stations from the Kentucky Mesonet (www.kymesonet.org), first-order automated stations from the National Weather Service (NWS; www.ncdc.noaa.gov/oa/ncdc.html), and Community Collaborative Rain, Hail and Snow Network Stations (CoCoRaHS), some of which recorded more than 350 mm of rain during the two-day period across portions of the region (Fig. 2).

The Kentucky Mesonet station in Bowling Green recorded the greatest rainfall intensity for the state, with 8.38 mm during a 5-min period, and 50.8 mm during an hour (Fig. 3). Bowling Green, Kentucky, also received the greatest amount of rainfall in the state with 258 mm, which broke the previous all-time two-day precipitation record for the state of 211 mm set during 6–7 December 1924. Moreover, Bowling Green received more than 120 mm each day, which ranks as the sixth (124.9 mm) and eighth (120.6 mm) greatest daily rainfall totals in Kentucky since 1900. According to the NWS office in Nashville, Tennessee, Camden, Tennessee, received the most rainfall in the state with 493 mm, which also set a new precipitation record. One CoCoRaHS station in Camden reported nearly 338 mm during a 24-h period, which was 7.62 mm shy of the all-time 24-h precipitation record for Tennessee. Nashville received more than 150 mm each day of the event, which ranked as the third-most (158.2 mm) and greatest (184.2 mm) 24-h rainfall accumulations of all time, and subsequently marked the wettest May on record for the city. In fact, many prior rainfall records that fell to the 1–2 May 2010 extratropical heavy precipitation event were originally produced by systems that were tropical in origin (e.g., Hurricanes Frederic and Katrina in 1979 and 2005, respectively).

Dating back to November 2009, antecedent precipitation across central Kentucky and Tennessee was as much as 300 mm below normal, which resulted in moderate drought conditions, according to the U.S. Drought Monitor. However, despite the relatively dry surface conditions, the intense rainfall that began 1 May resulted in runoff into nearby streams and rivers. Repeated heavy precipitation during the 48-h period ultimately helped produce 20 new flood-stage records within six river basins across the region. The Cumberland River in Nashville breached the major flood stage by 2 m, with a record crest of 15.6 m, which contributed to the historic flooding of the downtown area of Nashville.

The Hydrometeorological Design Studies Center is a branch of NOAA's NWS that is currently in charge of providing precipitation frequency estimates for the United States (HDSC; www.nws.noaa.gov/oh/hdsc/index.html). According to the HDSC, the estimated precipitation frequency outcome for a large portion of western Tennessee was

AFFILIATIONS: DURKEE, CAMPBELL, BERRY, JORDAN, GOODRICH, MAHMOOD, AND FOSTER—Meteorology Program, Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky
CORRESPONDING AUTHOR: Joshua D. Durkee, Department of Geography and Geology, Western Kentucky University, 1906 College Heights Blvd., Bowling Green, KY 42101
E-mail: joshua.durkee@wku.edu

DOI:10.1175/BAMS-D-11-00076.1

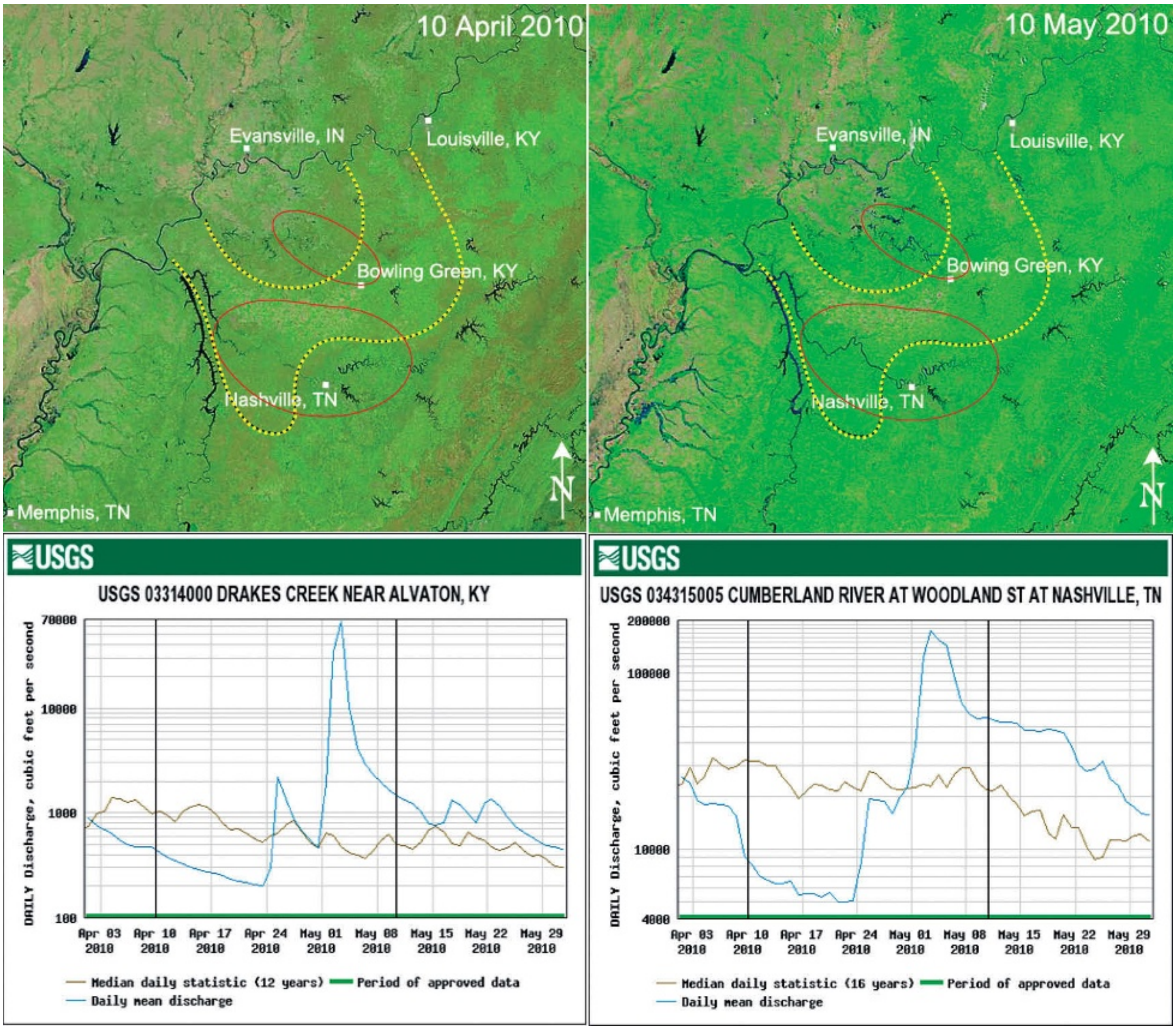


Fig. 1. (Top) Modis Terra 1000-m false color RGB image, highlighting changes in the waterways between 10 Apr and 10 May 2010 as a result of the 1–2 May 2010 record precipitation and flood event across the mid-South. Red circles highlight changes in the visibility of the waterways before and after the event. Dotted lines demarcate local karst boundaries. (Bottom) Daily stream discharge for (left) Drakes Creek near Alvaton and Bowling Green, Kentucky, and (right) the Cumberland River in Nashville, Tennessee. Bold vertical black lines mark the dates of the satellite imagery.

a 1,000-year event. Recurrence intervals across south-central Kentucky counties were as high as 200 years. Unfortunately, the intense rainfall and resultant widespread flood led to 26 fatalities (4 in Kentucky and 22 in Tennessee), more than $2 billion dollars in private-property damage, and more than 11,000 ill-affected structures across the region (Fig. 4). Urbanized and densely populated areas, including nearby or within Nashville and Memphis, Tennessee, were among the hardest hit in terms of flood-related damages and fatalities.

Given the widespread disastrous outcomes left behind from this particularly rare, heavy precipitation event for this region, it is imperative that we identify the synergy of the leading atmospheric and land-surface processes that contributed to the rainfall component of this event. The purpose of this discussion is to provide a brief analysis of the key synoptic-scale features and other atmospheric and land-surface constituents that played important roles in the development, magnitude, and mesoscale distribution of this historic rainfall event.

SYNOPTIC ANALYSIS. The upper-air data used in this analysis included North American Regional Reanalysis (32 km x 32 km) (NARR) 250- and 500-hPa heights and winds, and 850-hPa heights, winds, and temperatures, and were analyzed using the Integrated Data Viewer provided by Unidata (IDV; www.unidata.ucar.edu/software/idv). The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Data were used to analyze 2.5° x 2.5° gridded 925-hPa winds, 500-hPa heights, and precipitable water (PW) data using geographic information systems (GIS). Standardized anomalies of daily composite 500-hPa heights and PW fields were calculated from the NCEP/NCAR data using 21-day centered means from a 30-yr base period of 1980–2009, given by

$$\sigma_A = \frac{X - \mu}{\sigma},$$

where X is the observed grid-point value, μ is the centered 21-day climatological mean, and σ is the standard deviation. Derived total precipitable water (TPW) was analyzed from Special Sensor Microwave Imager/Advanced Microwave Scanning Radiometer for EOS (SSMI/AMSRE) via the Morphed Integrated Microwave Imagery (MIMIC-TPW) product, produced by the Cooperative Institute of Meteorological Satellite Studies at the University of Wisconsin—Madison. Precipitation data were analyzed from Kentucky Mesonet, NWS first-order, and CoCoRaHS observations, and level 2 radar reflectivity (KOHX; Nashville).

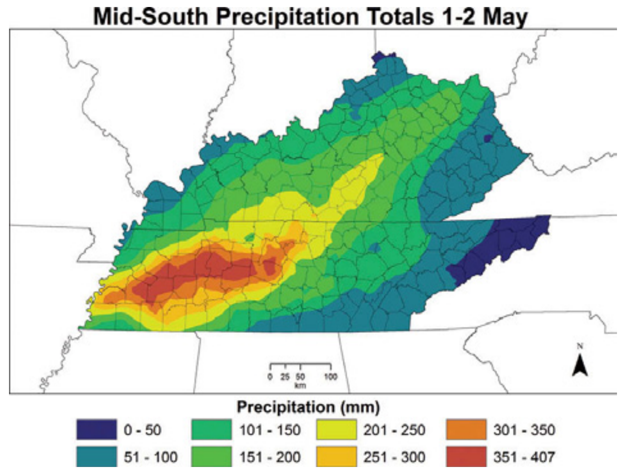


Fig. 2. Multisource precipitation map showing rainfall accumulations across Kentucky and Tennessee, observed from the Kentucky Mesonet, NWS first-order stations, and CoCoRaHS networks.

Leading up to the event, the synoptic circulation (not shown) during 29–30 April 2010 was characterized by a broad, developing trough and subtropical ridge pattern over the western and eastern United States, respectively. This upper-air circulation initially forced a steady low-level south-southwesterly surge of considerably warm, moist air across the Tennessee–Kentucky region. According to the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model, backward air-parcel trajectories starting from Bowling Green and Camden at 1,296 and 1,280 m AMSL (~845 hPa), respectively, originated from the Intertropical Convergence Zone (ITCZ) on the Pacific Ocean side of Central

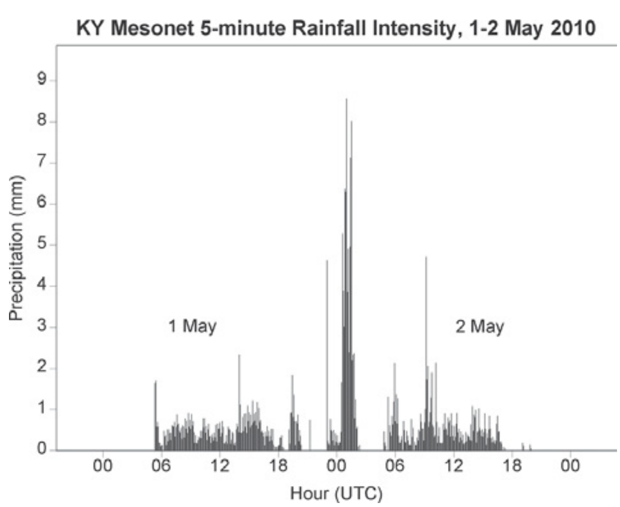


Fig. 3. Kentucky Mesonet 5-min rainfall rates over Bowling Green, Kentucky, during 1–2 May 2010.

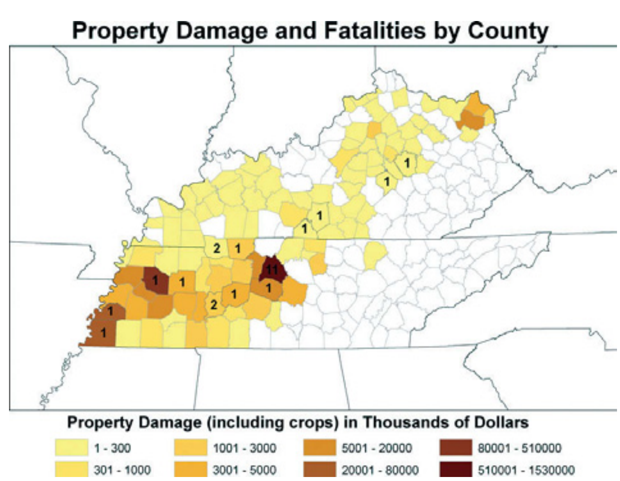


Fig. 4. Casualties, and property and crop damages by county during 1–2 May 2010.

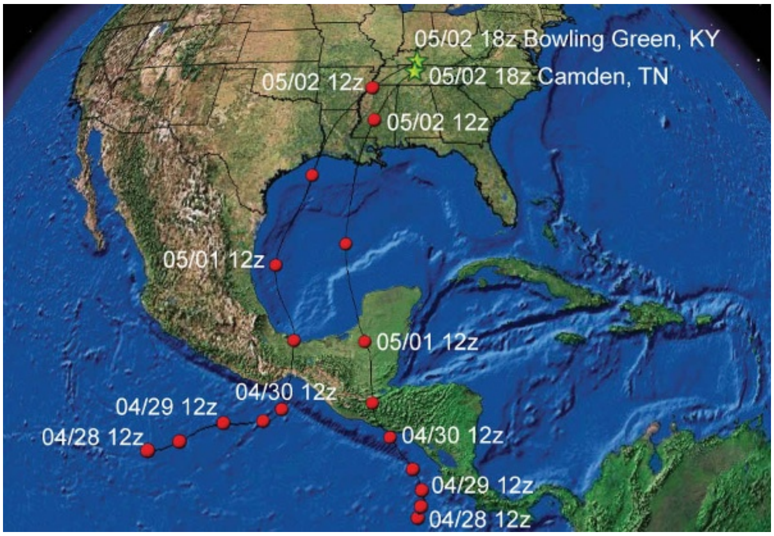


Fig. 5. NOAA HYSPLIT backward air-parcel trajectories starting from Bowling Green, Kentucky, and Camden, Tennessee, at 1,296 and 1,280 m AMSL (~845 hPa), respectively, from 2 May 2010 at 1800 UTC to 29 Apr 2010 at 1200 UTC.

America as early as 29 April 1200 UTC (Fig. 5). As the south-southwest/north-northeast oriented low-level, tropical Pacific originating moisture axis set up just east of the Mississippi River, surface dew points across the region increased from ~ 7° to 20°C during this period. Surface temperatures of around 25°C were observed as far north as south-central Wisconsin and Lower Michigan, in association with the surface low-pressure circulation over the northern Great Plains and its attendant warm frontal boundary.

Farther downstream, a closed upper-level low was positioned over the Gulf of St. Lawrence in eastern Canada, and the atmospheric pattern was suggestive of a negative phase of the North Atlantic Oscillation (NAO), as indicated by relatively strong ridging across the northern Atlantic. The negative NAO inhibited the eastward progression of the upstream synoptic pattern and played an important role in amplifying the meridional component of the trough and ridge across the United States. Together, the concatenation of these synoptic processes sufficiently preconditioned the atmospheric environment over the mid-South region for the record precipitation and catastrophic flood event.

By 1 May 2010, the meridional upper-level circulation across North America and the northern Atlantic had intensified into an anomalously high-amplitude synoptic wave pattern. Daily composite standardized height anomalies ranged from −6 to +6 across the midlevel trough and ridge, respectively (Fig. 6). Figure 7 shows daily composite circulation features at 250, 500, and 850 hPa for 1 May (left column) and 2 May (right column). During 1 May, the 250-hPa circulation exhibited a jet-stream wind maximum downstream of the positively tilted trough axis that extended from the northern Great Plains through the Four Corners region, and diffluent southwesterly and westerly flow over the mid-South. In response to the deepening trough and increasing jet-stream winds, a corridor of southwesterly 850-hPa winds advecting deep tropical moisture—referred to as an atmospheric river (for a thorough discussion on the nature of the atmospheric river during the 1–2 May 2010 event, see Moore et al. 2011)—strengthened along and east of the Mississippi River Valley (see also Fig. 5). At the surface and just upstream of the warm sector, a weak low-pressure center developed in Arkansas, along a southwest/northeast oriented surface stationary boundary. Downstream across portions of western and central Tennessee and Kentucky, and into

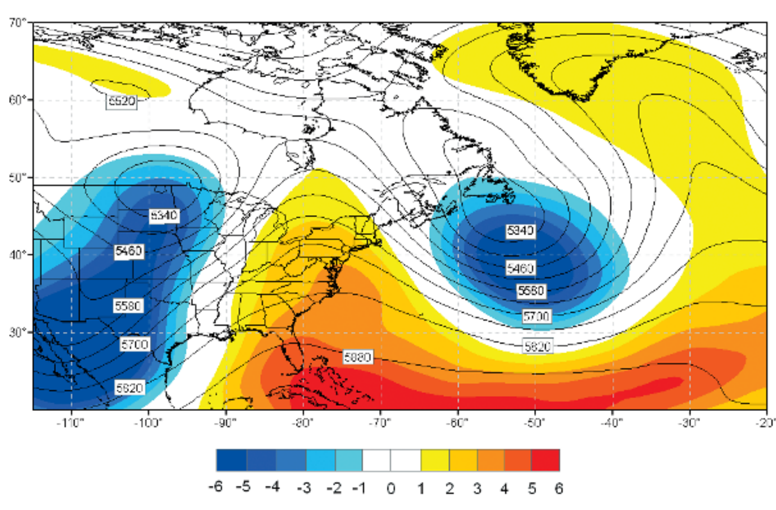


Fig. 6. NCEP/NCAR Reanalysis data showing daily composite 500-hPa heights (m) and standardized anomalies for 1 May 2010.

central Indiana, a PW axis with the same orientation as the surface boundary contained values of 37–40 mm, which were +2 standard deviations above normal for this time (Fig. 8a). Dew points across western and central Tennessee and Kentucky were around 25° and 21°C, respectively. Together, these synoptic-scale

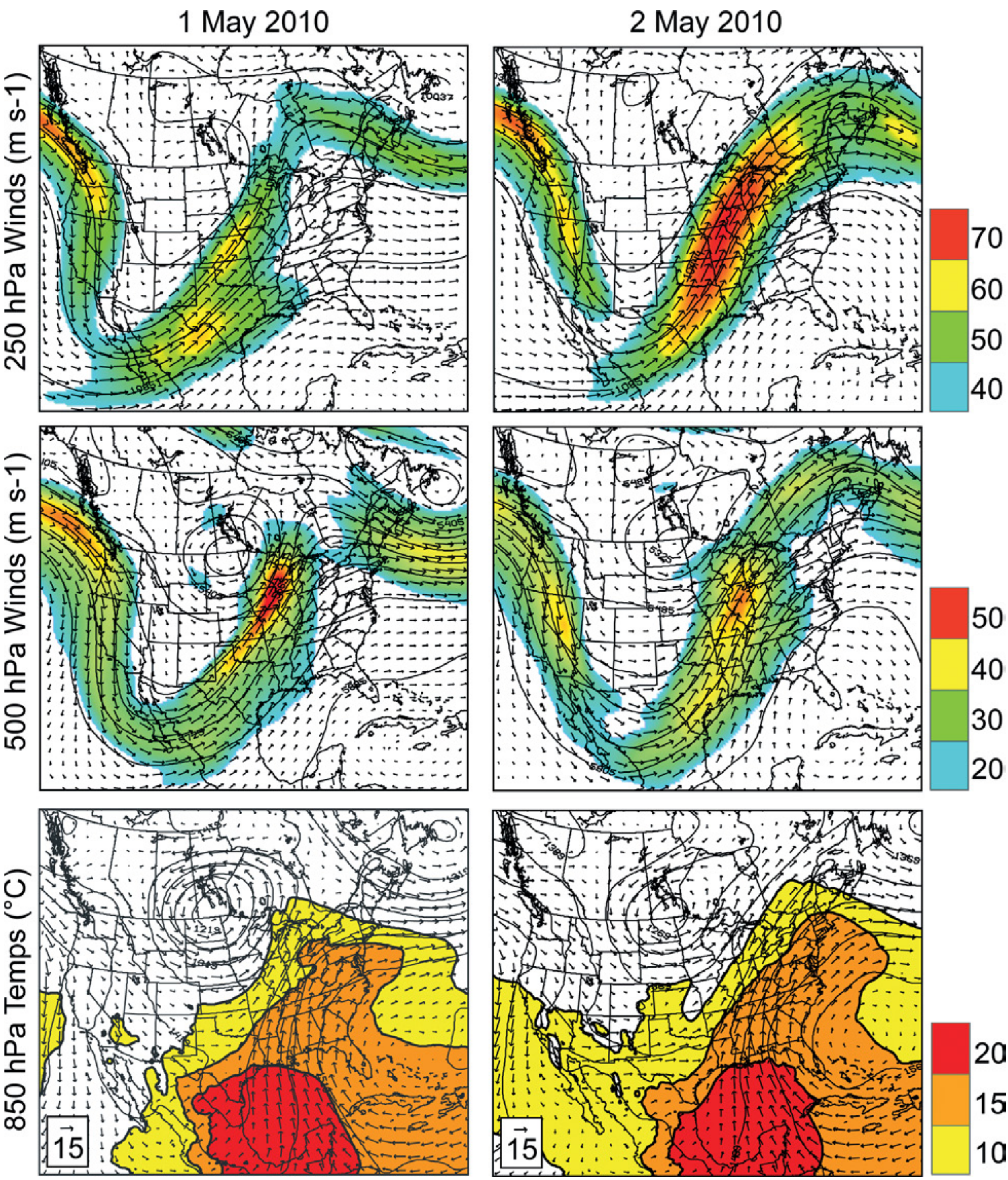


Fig. 7. North American Regional Reanalysis (NARR) data showing daily composite 250- and 500-hPa heights (m) and winds (m s^{-1}), and 850-hPa heights (m), winds (m s^{-1}), and temperatures (starting at 10°C; 5° intervals) for (left column) 1 May and (right column) 2 May 2010.

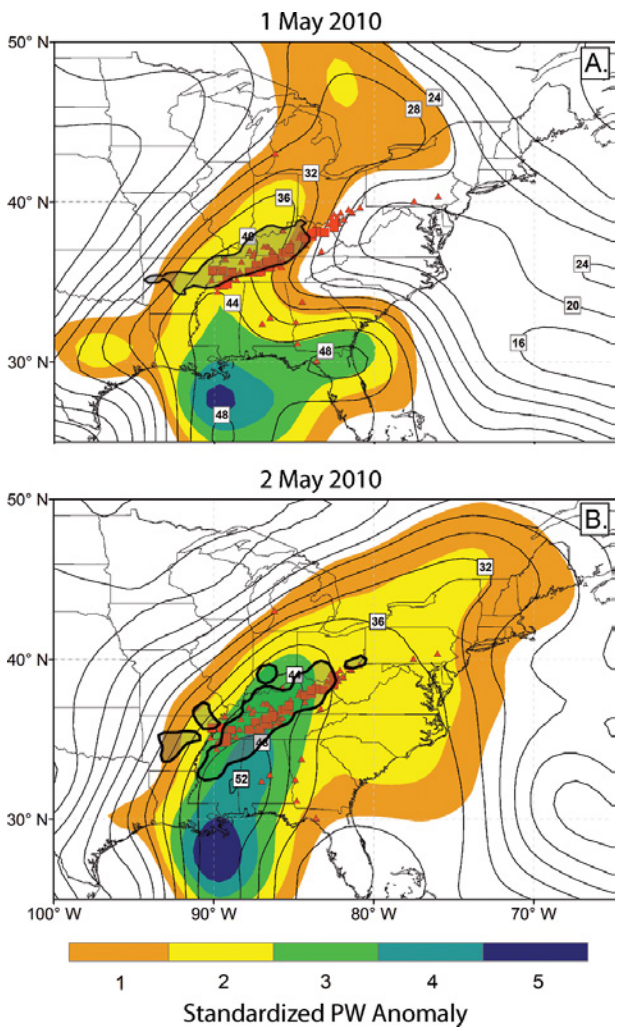


Fig. 8. NCEP/NCAR Reanalysis data showing daily composite precipitable water (mm) (thin contours) and standardized anomalies (shaded) for (a) 1 May and (b) 2 May 2010. Bold outlined areas demarcate areas with upward vertical motion with the outer extent starting with omega values of −0.3 Pa s^{-1}. Triangles indicate the locations of precipitation accumulation records for the month of May. Squares show the locations of all-time 24-h precipitation accumulation records.

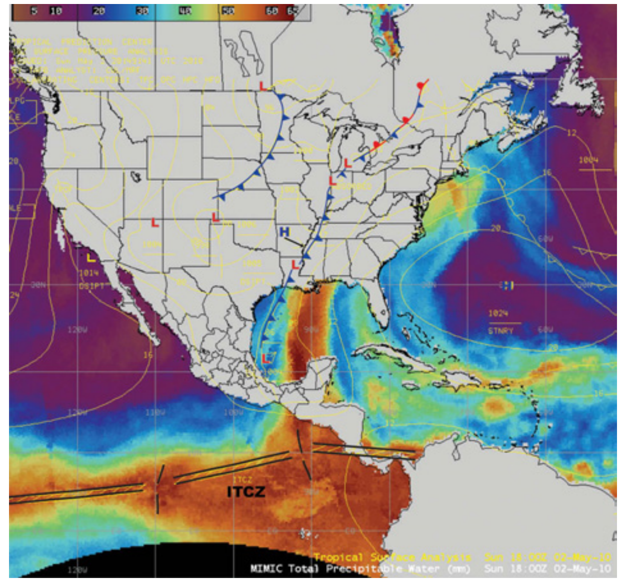


Fig. 9. Tropical surface analysis, and MIMIC-total precipitable water (mm) product (over oceans only).

processes, particularly the continuous flux of deep tropical moisture across the mid-South, in part, aided in sufficient forcing supportive for large-scale vertical ascent and heavy rainfall across the region.

By 2 May 2010, the amplitude of the upper-air circulation intensified with relatively little eastward progression (see Fig. 7, right column). Downstream of the 250-hPa trough that continued to deepen across the intermountain west, the core of the jet strengthened along the poleward component of the amplified and anomalous ridge across the east and southeast United States. While the midlevel winds began to increase over the mid-South, the surface frontal boundary slowly began its initial advancement across the Mississippi River. During this time, the low-level winds strengthened and continued to advect deep tropical moisture across the region. The tropical surface analysis and MIMIC-TPW product shown in Fig. 9 highlights the rich plume of atmospheric moisture with a confined axis that extended from the ITCZ, out in advance of the slow-moving surface front. At this time, PW values within the PW anomaly axis that extended through Nashville and Bowling Green increased appreciably by nearly 10 mm—an amount +2 to +4 standard deviations above normal (see Fig. 8b). As the cold-frontal boundary slowly advanced, slow-moving regenerative thunderstorms continued to develop within the sufficiently moist, unstable warm sector across the mid-South.

Overall, from a synoptic-scale perspective, the key ingredients for preconditioning the atmosphere for any precipitation event include sufficient lift of relatively moist air, with enough instability to maintain the development and maintenance of the precipitating system. In the case of the 1–2 May 2010 record rainfall across the mid-South, an amplified upper-air circulation that initially developed on 29 April 2010 resulted in a particularly anomalous 500-hPa trough and ridge across Mexico and the intermountain west and the Caribbean Sea, respectively. As a consequence of the placement and magnitude of these upper-air features, the Pacific ITCZ-originating atmospheric river advected historic amounts of PW poleward across the mid-South. Daily composite PW values near Nashville ranked below the 25th percentile between 28 and 30 April before a sizeable increase to above the 75th and 99th percentiles on 1 and 2 May, respectively (Fig. 10a). In fact, Fig. 10b shows that PW values increased by up to +2 standard deviations above normal just between 1 and 2 May, when many of the aforementioned precipitation records were set. Meanwhile, downstream over the Atlantic Ocean, an anomalous closed upper-low circulation and negative NAO (Atlantic ridging) likely enhanced the amplification of the upstream synoptic wave pattern and helped to inhibit the eastward wave progression. Downstream of the quasistationary/slow-moving surface front along the lower Mississippi River, numerous mesoscale convective systems (MCSs) developed across similar areas within the conditionally unstable and anomalously warm moist sector and repeatedly produced markedly intense rain rates.

While the heavy rainfall during the course of this event was largely derived from sufficient lift and instability within a particularly deep, anomalous moist layer that originated over the tropical Pacific ITCZ, the synergy of other important atmospheric and land-surface processes on different levels and scales also aided heavy MCS rainfall across the region. Maddox et al. (1979) and Doswell et al. (1996) (among other studies) highlight the importance of system propagation and cell motion speed, as well as the orientation of the surface frontal boundary and the upper-level winds with respect to heavy rainfall and flood potential. Both studies show that flood potential increases dramatically when cell motion is parallel to both the upper-level circulation and a slow-moving frontal boundary.

During 1–2 May, rainfall totals were exacerbated by storm motions that were closely parallel to both the upper-air circulation and surface quasistationary/slow-moving cold-frontal boundary. Corfidi (2003) describes the role of gust-front orientation with respect to concurrent upwind and downwind system propagation within environments of largely unidirectional mean winds. With the 1–2 May 2010 event, the large-scale circulation was conducive for forward-propagating linear storm structures that produced upwind outflow boundaries that led to steady back-building and repeated cell development across the same areas. According to the 1 May 1130 UTC KOHX Nashville NWS severe weather bulletin (nearly 5 h into the event), estimated cell motion was out of the southwest at 17.5 m s^{-1}. The storm vectors were oriented nearly parallel to the quasistationary surface boundary, with estimated mean 0–6-km winds out of the south-southwest at 19.5 m s^{-1}. Meanwhile, animated radar reflectivity indicated that MCS propagation was toward the east-southeast at roughly half the storm motion and mean 0–6 km wind magnitudes (Fig. 11a–d). By 2 May 1153 UTC, the KOHX Nashville NWS severe-weather bulletin estimated that cell motion was more oriented with the surface front out of the southwest at 20.1 m s^{-1}. As a result, many locations were inundated by heavy rains from regenerative storms (Fig. 11e–h).

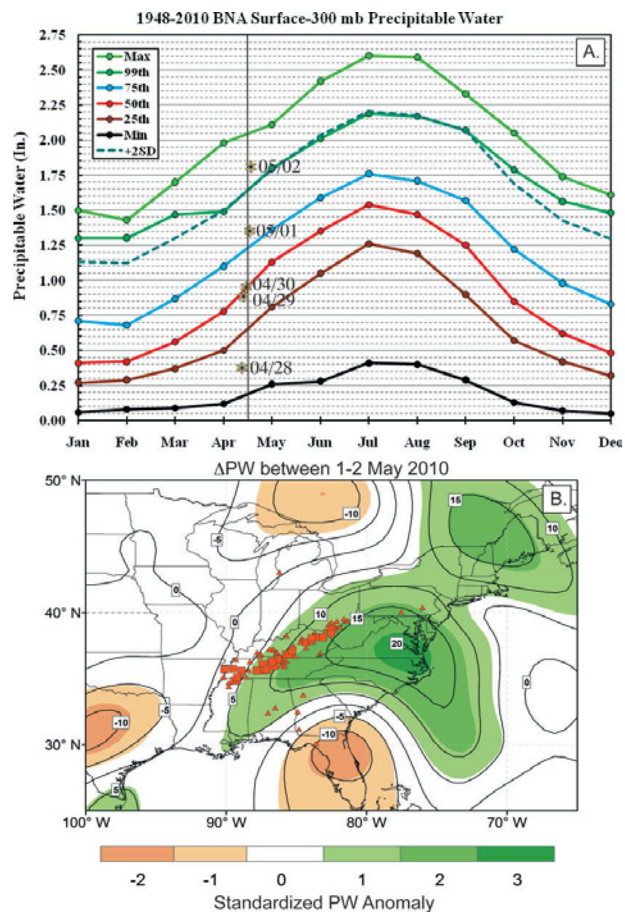


Fig. 10. (a) Annual PW (in.) climatology for Nashville, Tennessee (www.crh.noaa.gov/unr/?n=pw). Yellow asterisks indicate daily composite NCEP/NCAR Reanalysis PW values for the grid point closest to Nashville, Tennessee, for 28 Apr–2 May 2010. (b) As in Fig. 8b except for the change in PW (mm) and standardized PW anomalies between 1 and 2 May 2010.

In addition to synoptic and mesoscale atmospheric forcing, we suggest that mesoscale land-surface/atmosphere interactions may have also played an

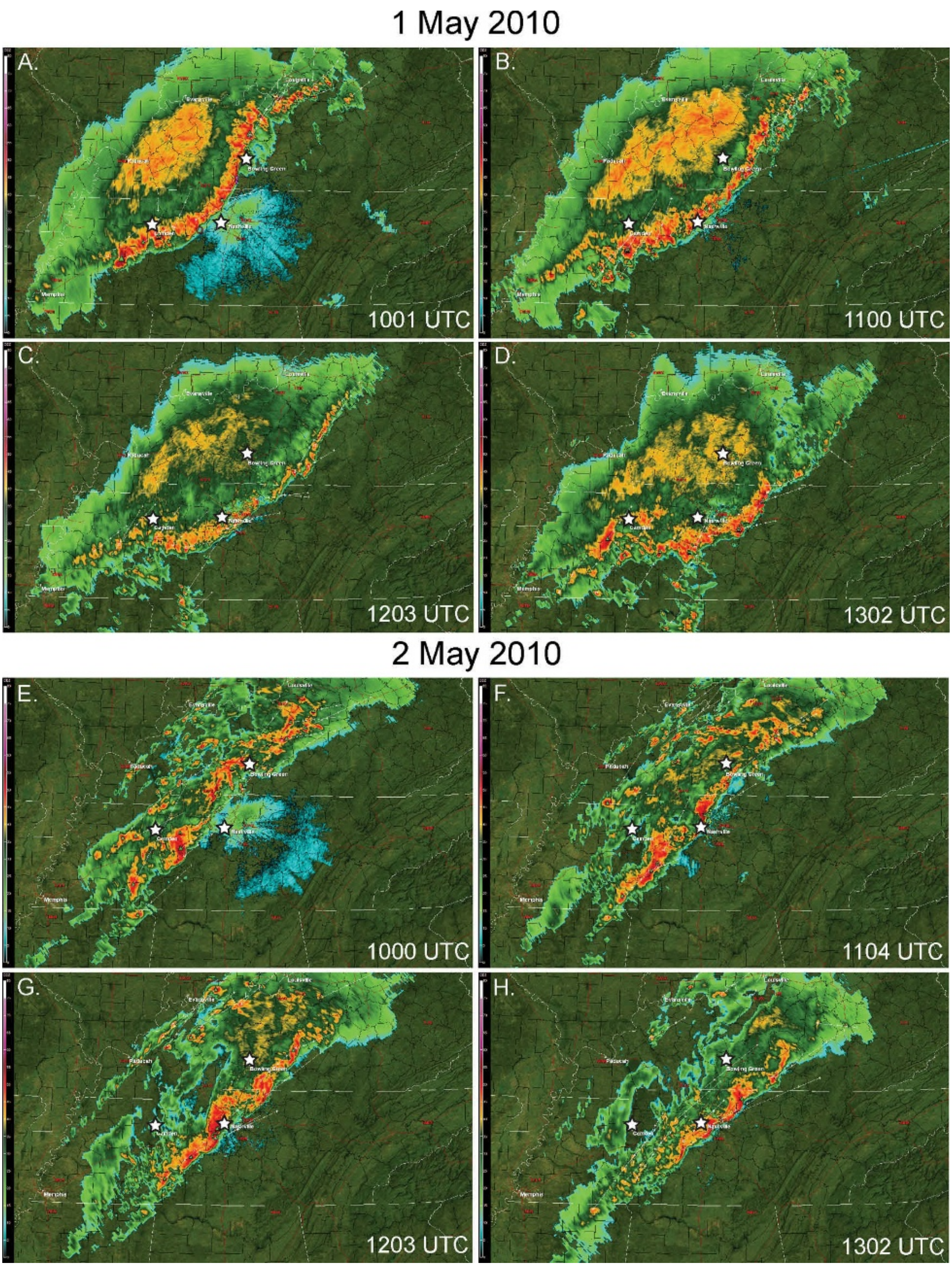

1 May 2010
A.
1001 UTC
B.
1100 UTC
C.
1203 UTC
D.
1302 UTC
2 May 2010
E.
1000 UTC
F.
1104 UTC
G.
1203 UTC
H.
1302 UTC

Fig. 11 (opposing page). KOHX Nashville NWS level 2 radar reflectivity shown using Gibson Ridge Software (www.grlevelx.com) for (a)–(d) 1 May 2010 during 1001, 1100, 1203, and 1302 UTC, respectively, and (e)–(f) 2 May 2010 during 1000, 1104, 1203, and 1302 UTC, respectively. From west to east (left to right), white stars mark the locations of Camden, Tennessee; Nashville, Tennessee; and Bowling Green, Kentucky, respectively.

important role in the spatial distribution of the rainfall over the region. Specifically, some locations that received the heaviest localized precipitation (e.g., Camden, Nashville, and Bowling Green) are located along or adjacent to well-developed karst hydrogeologic boundaries (see Figs. 1 and 11). The karst landscape, due to its geomorphologic characteristics, allows relatively rapid draining of surface water and with time, subsequent development of relatively dry or even drought conditions. Thus, the hydrogeologic settings of a well-developed karst environment can also alter local soil-moisture distributions, which can manifest in important land-surface/atmosphere interactions. This is not surprising, because it is also well known that heterogeneity in soil-moisture distribution and wet–dry transitions can promote localized mesoscale circulations and subsequent convection.

In a sensitivity analysis for precipitation over karst landscapes in Kentucky, Leeper et al. (2011) have shown that even under moderate-to-strong synoptic circulations, adjacent wet/dry land-surface conditions can modify the energy balance, the evolution of the planetary boundary layer, mesoscale circulations, and subsequent location of convection. Therefore, it is plausible to consider that relatively dry antecedent conditions (dating back to November of the previous year) near karst land-surface boundaries across west-central Kentucky and Tennessee provided this type of relative wet–dry transition and potentially offered a favorable localized environment for enhanced convection and precipitation during the course of this event. Given the scope of this study, the extent to which enhanced convection and precipitation during the 1–2 May 2010 historic precipitation event was influenced by local karst hydrogeologic land-surface/atmosphere interactions will be the focus of future work.

In summary, it is not uncommon to see a coincident broad large-scale trough and ridge configuration across the western and eastern United States during the spring transition season, respectively. While this type of synoptic circulation set the initial foundation for the historic 1–2 May 2010 mid-South heavy precipitation event by preconditioning the region via destabilization and anomalous moistening of the atmosphere, the synoptic pattern itself was not uncommon with respect to heavy rain and flash-flood potential. The results presented here are consistent with other studies that examined atmospheric aspects of heavy precipitation events [e.g., Grumm and Hart (2001b) and Hart and Grumm (2001b)]. According to the classic study by Maddox et al. (1979) that examined large-scale atmospheric aspects of flash floods, the synoptic and mesoscale setup from which the historic mid-South flood of 2010 was spawned is relatively common [Fig. 12; cf., Maddox et al. (1979), Fig. 6]. What makes the 2010 event unique is that the magnitude and quasistationary nature of the synoptic pattern was such that a continuous fetch of water vapor from the tropical Pacific ITCZ supplied numerous, long-lasting MCSs with training cells, which resulted in widespread record rainfall totals (see Fig. 8). Lastly, interactions between the local karst land-surface across the region and the atmosphere may have also played a role in determining the location of some of the heavy rainfall.

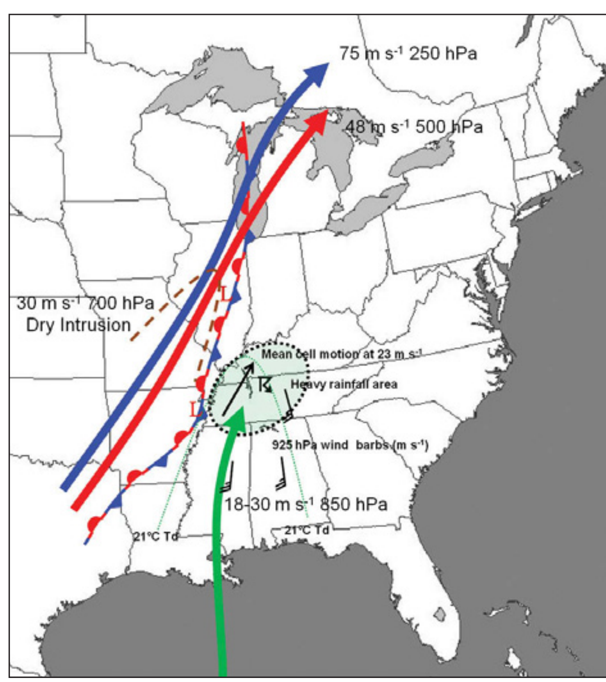


Fig. 12. Schematic composite of the synoptic features during 1–2 May 2010.

ACKNOWLEDGMENTS. We would like to acknowledge Tom Salem, Jeff Waldstreicher, and two anonymous reviewers for their insightful comments, which helped improve the manuscript. We would also like to thank Anthony Wimmers, Christopher Velden, Scott Bachmeier, and the Cooperative Institute of Meteorological Satellite Studies at the University of Wisconsin—Madison for their assistance with the satellite data used in this study.

FOR FURTHER READING

Burt, C. C., and M. Stroud, 2004: *Extreme Weather*. W.W. Norton and Co., 304 pp.

Chen F., and R. Avissar, 1994: Impact of land-surface moisture variability on local shallow convective cumulus and precipitation in large-scale models. *J. Appl. Meteor.*, **33,** 1382–1401.

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

Corfidi, S. F., 2003: Cold pools and MCS propagation: Forecasting the motion of downwind-developing MCSs. *Wea. Forecasting,* **18,** 997–1017.

Doswell III, C. A., H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560–581.

Draxler, R. R., and G. D. Rolph, 2011: HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY website. NOAA Air Resources Laboratory. [Available online at http://ready.arl.noaa.gov/HYSPLIT.php.]

Groves, C., C. Bolster, and J. Meiman, 2005: Spatial and temporal variations in epikarst storage and flow in south central Kentucky's Pennyroyal Plateau Sinkhole Plain. *U.S. Geological Survey Scientific Investigations Report 2005*, 64–73.

Grumm, R. H., and R. E. Hart, 2001a: Standardized anomalies applied to significant cold season weather events: Preliminary findings. *Wea. Forecasting*, **16**, 736–754.

——, and ——, 2001b: Anticipating heavy rainfall: Forecast aspects. Preprints, *Symp. Precipitation Extremes: Prediction, Impacts, and Responses*, Albuquerque, NM, Amer. Meteor. Soc., 66–70.

Hart, R. E., and R. H. Grumm, 2001a: Using normalized climatological anomalies to rank synoptic-scale events objectively. *Mon. Wea. Rev.*, **129**, 2426–2442.

——,and ——, 2001b: Anticipating heavy rainfall events: Forecast aspects. Preprints, *Symp. Precipitation Extremes: Prediction, Impacts, and Responses*, Albuquerque, NM, Amer. Meteor. Soc. 271–275.

Hydrometeorological Design Studies Center, cited 2010: Precipitation frequency data server. [Available online at www.nws.noaa.gov/oh/hdsc/index.html.]

Kalnay, E., and Coauthors, 1996: The NCEP–NCAR 40-year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77**, 437–471.

Kentucky Mesonet, cited 2010: Monthly climatological summary. [Available online at www.kymesonet.org/historical_data.php.]

Kusselson, S., L. Zhao, R. Kuligowski, S. Kidder, J. Forsythe, and A. Jones, 2010: The Tennessee flood of May 2010: A satellite perspective. *35th Conf. of the National Weather Association*, Tucson, AZ.

Leeper, R., R. Mahmood, and A. I. Quintanar, 2011: Influence of karst landscape on planetary boundary layer atmosphere: A weather research and forecasting (WRF) model-based comparison. *J. Hydrometeor.,* **12**, 1512–1529.

Maddox, R. A., C. F. Chappell, and L. R. Hoxit, 1979: Synoptic and meso-alpha scale aspects of flash flood episodes. *Bull. Amer. Meteor. Soc.,* **60,** 115–123.

Mesinger, F., and Coauthors, 2006: North American regional reanalysis. *Bull. Amer. Meteor. Soc.* **87**, 343–360.

Moore, B. J., P. J. Neiman, F. M. Ralph, and F. E. Barthold, 2011: Physical processes associated with heavy flooding rainfall in Nashville, Tennessee, and vicinity during 1–2 May 2010: The role of an atmospheric river and mesoscale convective systems. *Mon. Wea. Rev.*, **140**, 358–378.

National Climatic Data Center, cited 2010: Storm events database. [Available online at www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~storms.]

National Weather Service, cited 2010: Record floods of greater Nashville: Including flooding in Middle Tennessee and Western Kentucky, May 1–4, 2010. 93 pp. [Available online at www.nws.noaa.gov/os/assessments/pdfs/Tenn_Flooding.pdf.]

Rolph, G. D., 2011: Real-time Environmental Applications and Display System (READY) website. NOAA Air Resources Laboratory. [Available online at http://ready.arl.noaa.gov.]

Taylor, C. M., D. J. Parker, and P. P. Harris, 2007: An observational case study of mesoscale atmospheric circulations induced by soil moisture. *Geophys. Res. Lett.*, **34,** L15801, doi:10.1029/2007GL030572.

Wimmers, A. J., and C. S. Velden, 2011: Seamless advective blending of total precipitable water retrievals from polar-orbiting satellites. *J. Appl. Meteor. Climatol.*, **50**, 1024–1036.

TWO TIME SCALES FOR THE PRICE OF ONE (ALMOST)

BY LISA GODDARD, JAMES W. HURRELL, BENJAMIN P. KIRTMAN, JAMES MURPHY, TIMOTHY STOCKDALE, AND CAROLINA VERA

Although differences exist between seasonal- and decadal-scale climate variability, predictability, and prediction, investment in observations, prediction systems, and decision systems for either time scale can benefit both.

While some might call Decadal Prediction the new kid on the block, it would be better to consider it the latest addition to the Climate Prediction family. Decadal Prediction is the fascinating baby that all wish to talk about, with such great expectations for what she might someday accomplish. Her older brother, Seasonal Prediction, is now less talked about by funding agencies and the research community. Given his capabilities, he might seem mature enough to take care of himself, but in reality he is still just an adolescent and has yet to reach his full potential. Much of what he has learned so far, however, can be passed to his baby sister. Decadal could grow up faster than Seasonal did because she has the benefit of her older brother's experiences. They have similar needs and participate in similar activities, and thus to the extent that they can learn from each other, their maturation is in some ways a mutually reinforcing process. And, while the attention that Decadal brings to the household might seem to distract from Seasonal, the presence of a sibling is actually healthy for Seasonal because it draws attention to the need for and use of climate information, which can bring funding and new research to strengthen the whole Climate Prediction family.

Just as if these were children, it will take an entire community, actually several communities, together with patience and dedication, to evolve and test seasonal and decadal prediction and determine and realize their potentials. Strong and healthy prediction systems are developed only by substantial investment, as are effective decision systems that can make use of them. In this essay, we argue that investments in observations, modeling, and research focused on either time scale benefit both.

Important differences do exist between decadal- and seasonal-scale climate variability, predictability, and prediction. First, and most obvious, there is the

AFFILIATIONS: GODDARD—International Research Institute for Climate and Society, The Earth Institute of Columbia University, Palisades, New York; HURRELL—National Center for Atmospheric Research, Boulder, Colorado; KIRTMAN—Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida; MURPHY—Met Office Hadley Centre, Exeter, United Kingdom; STOCKDALE—ECMWF, Reading, United Kingdom; VERA—CIMA/CONICET-Universidad de Buenos Aires/FCEyN, Buenos Aires, Argentina
CORRESPONDING AUTHOR: Lisa Goddard, International Research Institute for Climate and Society, The Earth Institute of Columbia University, 61 Route 9W, 228 Monell Bldg., Palisades, NY 10964-8000
E-mail: goddard@iri.columbia.edu

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-11-00220.1

In final form 27 November 2011

time scale. Seasonal prediction covers the next month to a year into the future and presents the information in terms of monthly or seasonal means. Decadal predictions, which are currently experimental, are being run 10 years into the future, and the information is being viewed mostly as annual to decadal averages. Second, the climate processes and/or phenomena that drive the variability on different time scales are different. For seasonal climate, the dominant driver is the El Niño–Southern Oscillation (ENSO) phenomenon. Variability in the tropical oceans outside the Pacific is important for regional climate variability, although ENSO can influence the Indian Ocean and tropical Atlantic Ocean variability also. For decadal-scale climate variability, the main oceanic drivers appear to sit in the midlatitude oceans; Pacific decadal variability (PDV) and Atlantic multidecadal variability (AMV) have their largest sea surface temperature (SST) expression outside the tropics, and this SST variability may be linked to much deeper oceanic processes compared to ENSO. However, the decadal patterns of decadal variability do extend into the tropical oceans, and it may be that much of their impact is communicated to the atmosphere through these tropical SST changes. In addition, the secular response to man-made changes in atmospheric composition (i.e., greenhouse gases and aerosols) is an important source of predictability on the decadal time scale, but less so on the seasonal time scale.[1] Finally, the decisions affected are different. Seasonal predictions are more relevant to management decisions, whereas decadal predictions could be useful to planning decisions.

So, how is it that two vastly different time scales could work so well together in a climate services and research perspective? Despite the obvious differences, there are also common, even complementary, elements. Where the synergy is greatest between seasonal predictions and the burgeoning research on decadal predictions is through their dependence on forecast systems. Both prediction efforts use the same type of general circulation models, and they make use of the same global observing systems. Beyond these common priority elements, however, a number of other aspects exist for which past, present, and future investments aimed at one time scale could benefit the other.

COMMON PRIORITIES. The need for adequate observational networks and improved dynamical models appears in almost every recommendation list related to predictive information that one is likely to encounter. Prediction systems are based on observations, models, and their connection through assimilation systems. The three together is the three-legged chair of prediction systems (NRC 2010). Any weak leg compromises the system, and improvements in one leg often lead to improvements in the other legs. Recent advances in ENSO prediction skill at the European Centre for Medium-Range Weather Forecasts (ECMWF) were accomplished by both improvements to their model and improvements to the ocean data assimilation system (Balmaseda et al. 2010). Additionally, hindcasts from the ECMWF forecast system have demonstrated the value of the Tropical Atmosphere Ocean (TAO) array of data buoys in the tropical Pacific Ocean; a dramatic drop in ENSO forecast error coincides with the completion of the array in the early 1990s (Stockdale et al. 2011). This error reduction is largest for forecasts initiated in February, when model biases in their model are minimum. This reveals the connections between these three elements of forecast systems: observations and their assimilation into models are crucial for prediction, but better models better elucidate the value of the observing network.

The quality of predictive climate information depends on the quality of models. Models are far from perfect in their discretized, parameterized representation of the climate system. Long-term commitment of resources to model and assimilation system development will pay off with improved climate information on all time scales. In order to address longstanding systematic model errors, the community needs to improve the diagnosis of key physical processes contributing to these errors (Jakob 2010). Many of the mean biases and variability biases that hamper predictions appear within the first few hours or days of the forecast; for example, characteristics like the diurnal cycle, important in warm-season precipitation, are often not well represented. Indeed, it is critical that our climate prediction systems simulate the statistics of regional weather with fidelity given that the upscaling of that weather becomes the seasonal-to-decadal mean and also that the weather characteristics (e.g., changing precipitation intensity or frequency) determine many of the impacts. To better represent the temporal characteristics of the climate, forecast systems must be developed and tested across a range of time scales, which also brings the potential for stronger collaboration between the weather and climate prediction communities (Hurrell et al. 2009).

[1] When they occur, the impacts of explosive volcanic eruptions are important on both seasonal and multiannual time scales.

Furthermore, the development of climate models with better horizontal and vertical resolution should be a priority in order to improve the representation of coupled ocean–atmosphere variability (Guilyardi et al. 2004) and stratospheric effects on surface and tropospheric climate anomalies (Baldwin and Dunkerton 2001; Ineson and Scaife 2009). A priority is to implement the recommendations from the World Modeling Summit for Climate Prediction (Shukla et al. 2009), which calls for dedicated computational facilities 1,000–10,000 times more powerful than available today in order to address these issues.

Improvements of models and assimilation systems cannot proceed without an adequate observational network. The Global Climate Observing System (GCOS), including its many ocean and land components, is essential for improving seasonal prediction and developing decadal prediction. Real-time, complete observations provide the initial conditions to the predictions, and long, stable histories of ocean, atmosphere, and terrestrial climate that are necessary to verify the models' ability to make predictions. The observational network, originally designed for weather prediction, is only recently coming to grips with the additional requirements to collect, integrate, and sustain quality observations for climate time scales, but such a climate observing system is still far from being realized (GCOS 2010).

Individual observations—localized snapshots of the climate—have limited value until those data are integrated into the big picture that can be used for monitoring, initialization and/or verification of predictions, and diagnostic validation of models. Improved methods of analyzing the observations and assimilating them into climate models, including treatment of nonstationary observing systems,[2] would benefit research and prediction and provide a more stable monitoring platform for climate variability and change. Whether we consider salinity measurements in the open ocean or rain gauge data in most of the developing world, many climate data records are short relative to the long periods over which we need to test models. Ways of procuring and protecting climate observing systems are urgently needed. Additionally needed are increased international coordination on data handling standards and mutually applied methodologies to assemble, quality-check, reprocess, and reanalyze datasets, and to estimate their uncertainties. Such integration should be considered as an essential component of the climate observing system.

Ocean observations are particularly crucial as initial conditions for both seasonal and decadal prediction to obtain the predictability arising from slow changes in ocean circulation or heat content anomalies. Recent improvements to the coverage of the ocean with Argo floats provide unprecedented measurements of subsurface ocean temperature and salinity that are particularly relevant to the initialization of decadal predictions. As mentioned before, the TAO array of buoys is essential to the initialization of ENSO predictions and also to real-time monitoring of tropical Pacific variability. This is also important because the improved representation of the evolution of ENSO in models may improve simulation and prediction of Pacific decadal variability (Vimont et al. 2003). Additionally, we must quantify the benefit of satellite data to the initialization of the ocean, sea ice, snow cover, and soil moisture, which leads to information not only on how these elements contribute to seasonal prediction but also on their role in, and response to, decadal-scale variability.

LESSONS FROM SEASONAL PREDICTION RELEVANT TO DECADAL PREDICTION RESEARCH. Dynamical seasonal prediction systems are operational or quasi operational at a number of forecasting centers around the world (e.g., Saha et al. 2006; Stockdale et al. 2010) and have been since the early 1990s in some cases. Much of the experience gained by the seasonal prediction community over the last couple decades can be applied to decadal prediction. Some of these lessons inform our expectations of what can skillfully be predicted. For example, the prediction time horizon of a phenomenon is shorter than the time scale of the phenomenon. ENSO has a time scale of 3–7 years but is only predictable about 6–12 months in advance, perhaps as much as 18 months for very strong events (Chen et al. 2004). A similar result is emerging for AMV from "perfect model" studies (i.e., prediction experiments in which the model tries to predict itself), where ocean initial conditions may supply 10–15 years of predictability in upper-ocean heat content for certain regions, while the time scale of the variability is 20 years or longer (Branstator and Teng 2010; Msadek et al. 2010). This important aspect of the forecasts must be communicated to people considering the use of decadal predictions. However, while natural climate variability might be the dominant driver of time-varying anomalies out to a decade ahead for some regions, that natural climate

[2] Here, "nonstationary observing systems" refers to the geographic relocation of meteorological stations, or the change of instrumentation or technology used to monitor the weather and climate over time.

variability may not be predictable via initialization; in contrast, the slowly developing response to forced climate change, although of smaller magnitude at this time scale, may be predictable, at least in sign (e.g., Lee et al. 2006; Hurrell et al. 2010). Beyond a decade ahead, uncertainty in the response to external forcing becomes increasingly important as a source of prediction error, while decadal variability remains as a significant additional uncertainty, especially at regional scales (Hawkins and Sutton 2009).

Another insight of the seasonal prediction community is that the spatial scales of predictable signals for climate are much larger than the predictable spatial scales for weather. Spatially heterogeneous variability within a regional climate signal represents mainly unpredictable noise of more random, localized processes typically related to weather transients. The spatial scales of predictable climate signals typically increase for longer time scales, suggesting that the predictable spatial scales will be even larger for decadal variability than for seasonal variability. Thus, regional-scale climate information must serve as the basis for interpretation of the local scales at which many decision systems operate. If the regional-scale information is not represented correctly, the local-scale information and the associated uncertainty will be meaningless.

The quantitative assessment of predictable time horizons and spatial scales of any given prediction system requires hindcast studies, which are predictions of past variability. Large sets of hindcasts are necessary to estimate skill for both seasonal and decadal predictions, to sample different phases of variability (e.g., active vs quiet periods or positive vs negative anomalies), and to quantify and understand different sources of predictability. For seasonal climate, hindcasts, in combination with forecasts, allow climate scientists to calibrate and correct biases in their forecasts. Hindcasts also allow scientists from other fields and decision makers to assess the potential value of the forecast information. This will be more challenging for decadal prediction where few realizations of decadal variability exist in the instrumental record to test our ability to predict it. This again calls for improved data assimilation methodologies that can make the most of the limited historical data we have (Balmaseda et al. 2010).

All relevant data, including observations, hindcasts, and forecasts, must be publically accessible for researchers and decision makers to benefit from it. Ideally the data would be accompanied by information on how to interpret and use the data, and perhaps what might constitute its misuse. It has been demonstrated in a number of cases that greater access to data leads to wider use of the information, such as the availability of long model hindcasts from the Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction (DEMETER; see www.ecmwf.int/research/demeter/) (e.g., Palmer et al. 2004), and long simulation and hindcast runs from the Coupled Model Intercomparison Project phase 3 (CMIP3; Meehl et al. 2007) of the World Climate Research Programme (WCRP). Coordinated sets of decadal prediction hindcasts, such as those from ENSEMBLE-based predictions of climate changes and their impacts (ENSEMBLES; http://ensembles-eu.metoffice.com), are beginning to become available (van der Linden and Mitchell 2009) and will be part of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), but in order to interpret those data, one will also need access to relevant observations for bias correction and verification. Insufficient data access does remain an obstacle to wider use of the predictions. The World Meteorological Organization has designated a lead center of global producing centers (www.wmo.int/pages/prog/wcp/wcasp/clips/producers_forecasts.html), but those data are not openly available, and hindcast data are not available from several of the prediction systems that participate. On the other hand, the Working Group on Seasonal to Interannual Prediction (WGSIP) of the WCRP is currently coordinating the Climate-System Historical Forecast Project (CHFP), which will provide access to a wide range of hindcasts to evaluate subseasonal-to-decadal predictions of the climate system (Kirtman and Pirani 2009).

Additional important lessons that have been realized in the seasonal prediction community include the following: 1) forecasts must be issued probabilistically and require ensemble sizes that are commensurate with signal-to-noise levels of the temporal and spatial scales being predicted; 2) forecast quality must be assessed through a suite of metrics, as no single metric can cover all aspects of a forecast relevant to users (e.g., Jolliffe and Stephenson 2003; Hurrell et al. 2010); and 3) the climate system exhibits conditional skill (e.g., Goddard and Dilley 2005; Collins et al. 2006) and identification of the times when forecasts are likely to be more accurate leads to better decision systems (Goddard et al. 2010). These lessons are widely recognized in the seasonal prediction community, and they will apply to decadal predictions too.

The systematic use of seasonal prediction information is much less developed than the predictions themselves. In part this is because the prediction information evolved independently from its application. We now know that the content and format of the information required can be quite varied from sector to sector or even between regions for a given sector. While those who apply the climate information cannot determine the science just based on demand, their concerns, needs, and understanding of the information can inform where investment and communication of the science will have the greatest impact. Since considerable research and development is required to better incorporate climate information into decision systems, we will return to that as a point of investment in the future. The main lesson here is that there appears to be value in the cooperation between scientists and decision makers in developing decision systems for climate risk management.

INVESTMENTS IN SEASONAL PREDICTION THAT WILL BENEFIT DECADAL PREDICTION RESEARCH. Although seasonal prediction is a relatively mature practice, significant room for improvement remains. Continued investments in prediction techniques, including improvement to variability diagnostics and to the representation of interactions between climate system components, are necessary. This research can also advance decadal prediction. Additionally, climate information often must be quantitatively practical and meaningful at the scales on which decisions will be made. Approaches such as statistical downscaling of information in space and/or time or the transformation of coarser-scale climate information into other climate-related variables (flood risk, dry spells, maize yield, etc.) that are more congruent with societal concerns must be tested first in the seasonal prediction arena.

As stated early on, improved dynamical models is a common priority of climate prediction at all time scales. While work to improve dynamical models, which benefits all climate prediction time scales, is in progress, care and resources should be given to the estimation of quality and uncertainty, including allowance for model error, of existing forecast systems. Reliable estimates of uncertainty allow decision makers to account properly for risk. Given inevitable uncertainties in model predictions, the development of ensemble techniques to realistically sample the consequences of initial state and model errors is important. Decadal predictions will additionally require estimates of the anthropogenic contributions to forecast uncertainty and skill. The techniques that will allow us to estimate uncertainty for the whole range of climate prediction time scales will likely be developed in the context of seasonal prediction.

As a complement to prediction research, empirical and diagnostic studies of interannual climate variability must continue. Some aspects of ENSO are still not well understood, such as the interevent variability and why models fail to capture it. This includes the apparent decadal variability in the magnitude and frequency of ENSO events. It is thought that ENSO events can drive PDV through the atmospheric bridge (Alexander et al. 2002). However, it is primarily the ENSO events that exhibit the strongest SST anomalies in the central Pacific appear to drive aspects of PDV (Di Lorenzo et al. 2008). Improved understanding and better predictability of the details of ENSO events and their role(s) in PDV requires more investigation.

Improved climate predictions are of limited value to society, however, if that information cannot be readily incorporated into decision systems. Investment in collaboration and pilot projects that bring together researchers and decision makers with the diverse expertise necessary to design and implement such systems can yield benefits beyond the specific project. First, such projects build closer ties between the climate prediction specialists and other scientists and decision makers. This builds trust and better understanding of climate information, as well as increases the climate scientists' understanding of information needs and decision contexts. If this begins with seasonal prediction, there is opportunity to demonstrate performance over the recent past, through a feasible time frame in the present, and over the next few years. Building these relationships takes time, but the results can be realized in only a matter of years, rather than decades. As more information becomes available on decadal variability, these relationships can pay dividends through better communication and understanding, creating networks to develop useable information. Second, well-documented pilot projects (e.g., Brown et al. 2009; Ceccato et al. 2010) can inform other decision systems to allow climate risk to be managed more effectively by example, which increases the uptake of climate information, and can also guide the development, format, and delivery of climate information. The outcomes of pilot projects can be particularly beneficial to both the research community and other decision makers if they document the pitfalls and difficulties, not just the benefits, of using climate information. Third, to the extent that the increased uptake of climate prediction improves climate risk management at seasonal time scales, it will indirectly strengthen the capacity for using climate information on longer time scales.

In order to impact risk management, or to be realistically assessed by pilot projects, climate information must be supplied at appropriate spatial and temporal scales, address the appropriate variable(s), and contain reliable estimates of uncertainty. In most cases that information derives from regional-scale changes in the climate, at which the predictable climate signals at seasonal-to-decadal time scales operate; examples include worldwide teleconnection patterns associated with El Niño and La Niña events or the robust features of global warming. Thus, although local-scale information may be desired, it becomes more relevant within the large-scale context. The large scale carries both predictability and uncertainty, but downscaling to local scales, while potentially adding useful detail, contributes mainly to the uncertainty. This point is more easily demonstrated for seasonal prediction where, for example, forecasts for summer precipitation are made and can be verified each year at local to regional spatial scales (e.g., Gong et al. 2003). Examination of the spatial variation of local climate variability within the regional-scale climate signal becomes both an educational opportunity and a point for cooperative information development. The importance of this perspective will be even greater for decadal variability, however, where the predictable scales are likely to be larger, but the strength of the signal is likely to be smaller.

INVESTMENTS TOWARD DECADAL PREDICTION THAT WILL BENEFIT SEASONAL PREDICTION. The knowledge that global surface temperatures will continue to rise over the next several decades under any plausible emission scenario (Solomon et al. 2007) is now a factor in the planning of many organizations and governments. We know that climate changes will not be uniform around the globe, and natural regional and seasonal variations will have large impacts, especially over the next few decades or less. An important challenge, therefore, is to predict regional-scale climate variability and change. The decadal time scale is also widely recognized as an important time scale for endeavors such as water, agricultural, and land use planning (e.g., Vera et al. 2010).

The promise of decadal climate prediction is supported by observational evidence of decadal climate variability with significant regional impacts, the effects of anthropogenic and naturally forced climate change, evidence of potential skill from idealized predictability studies (Collins et al. 2006; Boer 2011), and pioneering attempts at predictions obtained by initializing climate models with observations (Smith et al. 2007). A number of efforts are underway, including internationally coordinated experiments of initialized decadal predictions (WCRP/CMIP5; Taylor et al. 2009) that are contributing to the IPCC AR5, and several national initiatives to provide decadal-scale climate information. However, many formidable challenges need to be addressed to build practical prediction systems capable of credible, useful decadal-scale information at regional scales (e.g., Murphy et al. 2010). The investments necessary to address many of these challenges can benefit seasonal prediction also.

Investments toward the prediction hindcast experiments will directly benefit seasonal as well as decadal prediction efforts. These are the first generation of decadal prediction hindcasts. Since, as discussed above, large sets of hindcasts are required to assess the quality of prediction systems, and since our ocean observations are limited going back into the twentieth century, production of decadal hindcasts will require innovative approaches to data assimilation and ocean-state estimation (Balmaseda et al. 2010). The assimilation methodology will be useful to extending seasonal prediction hindcasts further back in time, and also to improving initialization techniques going forward. Meanwhile, hindcasts generated by these efforts will be mutually beneficial. Decadal predictions already will predict the next season to a year on their way to prediction of the decade, thus increasing the suite of hindcasts for seasonal prediction. Seasonal predictions, and their hindcasts, could easily be extended further out into the future, which would increase the suite of experimental hindcasts for decadal prediction.

As we research decadal variability and the potential for prediction, we gain a better understanding and quantification of the role of longer-term variability in year-to-year impacts. Such understanding can be valuable to resource management in the face of longer-term expectations and planning, particularly in instances where the decadal-scale variations of the background climate modify the risk of exceeding certain climate thresholds or the frequency of extremes. A better understanding of some of the processes important for forcing decadal variability, and their improved representation in forecast models, also helps increase the quality of our seasonal forecasts. As discussed previously, better understanding of PDV and AMV is needed, including interactions with ENSO, and impacts on remote regions via teleconnections. Additional phenomena hypothesized to be sources of decadal predictability, such as the response to solar variability in the Pacific region or the thermodynamic influence of persistent upper-ocean heat content anomalies worldwide (Meehl et al. 2009), may also be important sources of regional predictability on seasonal time scales.

Decadal prediction has received much attention at least in part because of the high visibility and politicization of climate change projections. The fact that, over the span of a decade or two, variability may dominate anthropogenic trends regionally leads the climate risk management community to seek out decadal-scale climate information. Often "variability" is less politically charged than "change" and thus may represent a more desirable investment to some. Allowance for both the physical and political realities opens the door to adaptation that includes wise planning for the coming decade(s) and also preparation for year-to-year variability, which is where the largest impacts are most often experienced. Often resource management decisions are constrained by policy (Rayner et al. 2005), but since decadal variability and climate change are relatively new considerations for lawmakers, policy may be less restrictive for the longer-time-scale decisions. Thus, increased action and uptake of climate information on longer time scales may actually allow for policy reform that could make it less difficult for action on seasonal climate information. This of course assumes that the experience with longer-time-scale information leads to the perception of beneficial outcomes that resulted from the use of that information, and the most effective path to that is again the cooperative development of knowledge and decision systems (Lemos and Morehouse 2005).

CONCLUSIONS. The investments described will take considerable human and financial resources and a commitment to sustain them. Compared to the costs of adaptation, the costs of implementing these recommendations will be low, but substantial enough to highlight the need for international coordination to minimize duplication and share the lessons learned throughout the communities involved. These are actions that would be prudent even in the absence of climate change. However, given that climate change has focused global attention on the need for climate information, climate services could build adaptation incrementally through better awareness, preparedness, and resiliency to climate variability at all time scales.

Seasonal and Decadal should not be treated as competitors for the attention of the scientific community. Rather, we should enable them to "play nicely" together, in order to maximize the efforts invested in each.

ACKNOWLEDGMENTS. This essay grew out of white papers solicited by the World Climate Conference 3 for the expert sessions on seasonal prediction and decadal prediction. We gratefully acknowledge the input and perspectives of all our contributing authors: Y. Aitchellouche, O. Alves, W. Baethgen, M. Barange, G. Boer, M. Deque, M. Dettinger, Y. Ding, O. P. Dube, R. Graham, D. Griggs, P. Hayman, M. Kadi, V. Kattsov, N. Keenlyside, M. Kimoto, N. Kobysheva, A. Kumar, K. Kumar, W. Landman, R. Martínez, S. Mason, G. Meehl, V. Mehta, H. Meinke, P. Nobre, E. Odada, S. Parey, H. Pohlmann, J. Polovina, G. Poveda, A. Scaife, B. Seguin, D. Smith, O. Tomoaki, K. Trenberth, and W. T. Yun. We also thank Jeff Rosenfeld for his thoughtful suggestions on this essay.

REFERENCES

Alexander, M. A., I. Bladé, M. Newman, J. R. Lanzante, N.-C. Lau, and J. D. Scott, 2002: The atmospheric bridge: The influence of ENSO teleconnections on air–sea interaction over the global oceans. *J. Climate,* **15,** 2205–2231.

Baldwin, M. P., and T. J. Dunkerton, 2001: Stratospheric harbingers of anomalous weather regimes. *Science,* **294,** 581–584.

Balmaseda, M. A., and Coauthors, cited 2010: Initialization for seasonal and decadal forecasts. [Available online at www.oceanobs09.net/blog/?p=57.]

Boer, G. J., 2011: Decadal potential predictability of twenty-first century climate. *Climate Dyn.,* **36,** 1119–1133, doi:10.1007/s00382-010-0747-9.

Branstator, G., and H. Teng, 2010: Two limits of initial-value decadal predictability in a CGCM. *J. Climate,* **23,** 6292–6311.

Brown, C., E. Conrad, A. Sankarasubramanian, S. Someshwar, and D. Elazegui, 2009: The use of seasonal climate forecasts within a shared reservoir system: The case of Angat reservoir, the Philippines. *Climate Change Adaptation in the Water Sector,* F. Ludwig et al., Eds., Earthscan, 249–264.

Ceccato, P., I. N. S. Jaya, J. H. Qian, M. K. Tippett, A. W. Robertson, and S. Someshwar, 2010: Early warning and response to fires in Kalamantan, Indonesia. IRI Tech. Rep. TR10-14, 22 pp. [Available online at http://iri.columbia.edu/publications/id=1037.]

Chen, D., M. A. Cane, A. Kaplan, S. E. Zebiak, and D. Huang, 2004: Predictability of El Niño over the past 148 years. *Nature,* **428,** 733–736, doi:10.1038/nature02439.

Collins, M., and Coauthors, 2006: Interannual to decadal climate predictability in the North Atlantic: A multi-model-ensemble study. *J. Climate,* **19,** 1195–1203.

Di Lorenzo, E., and Coauthors, 2008: North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophys. Res. Lett.,* **35,** L08607, doi:10.1029/2007GL032838.

GCOS, 2010: Implementation plan for the Global Observing System for climate in support of the UNFCCC. WMO Rep. GCOS-138 (GOOS-184, GTOS-76, WMO/TD-1523), 180 pp. [Available online at www.wmo.int/pages/prog/gcos/Publication/gcos-138.pdf.]

Goddard, L., and M. Dilley, 2005: El Niño: Catastrophe or opportunity. *J. Climate,* **18,** 651–665.

——, and Coauthors, 2010: Providing seasonal-to-interannual climate information for risk management and decision-making. *Procedia Environ. Sci.,* **1,** 81–101, doi:10.1016/j.proenv.2010.09.007.

Gong, X., A. G. Barnston, and M. N. Ward, 2003: The effect of spatial aggregation on the skill of seasonal precipitation forecasts. *J. Climate,* **16,** 3059–3071.

Guilyardi, E., and Coauthors, 2004: Representing El Niño in coupled ocean–atmosphere GCMs: The dominant role of the atmospheric component. *J. Climate,* **17,** 4623–4629.

Hawkins, E., and R. Sutton, 2009: The potential to narrow uncertainty in regional climate predictions. *Bull. Amer. Meteor. Soc.,* **90,** 1095–1107.

Hurrell, J. W., G. A. Meehl, D. Bader, T. L. Delworth, B. Kirtman, and B. Wielicki, 2009: A unified modeling approach to climate system prediction. *Bull. Amer. Meteor. Soc.,* **90,** 1819–1832.

——, and Coauthors, 2010: Decadal climate prediction: Opportunities and challenges, *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society,* J. Hall, D. E. Harrison, and D. Stammer, Eds., Vol. 2, ESA Publ. WPP-306, 12 pp., doi:10.5270/OceanObs09.cwp.45.

Ineson, S., and A. A. Scaife, 2009: The role of the stratosphere in the European climate response to El Niño. *Nat. Geosci.,* **2,** 32–36.

Jakob, C., 2010: Accelerating progress in global atmospheric model development through improved parameterizations: Challenges, opportunities, and strategies. *Bull. Amer. Meteor. Soc.,* **91,** 869–875.

Jolliffe, I. T., and D. B. Stephenson, 2003: *Forecast Verification: A Practitioner's Guide in Atmospheric Science.* John Wiley and Sons, 240 pp.

Kirtman, B., and A. Pirani, 2009: The state of the art of seasonal prediction: Outcomes and recommendations from the First World Climate Research Program Workshop on Seasonal Prediction. *Bull. Amer. Meteor. Soc.,* **90,** 455–458.

Lee, T. C. K., F. W. Zwiers, X. Zhang, and M. Tsao, 2006: Evidence of decadal climate prediction skill resulting from changes in anthropogenic forcing. *J. Climate,* **19,** 5305–5318.

Lemos, M. C., and B. J. Morehouse, 2005: The co-production of science and policy in integrated climate assessments. *Global Environ. Change,* **15,** 57–68.

Meehl, G. A., C. Covey, K. E. Taylor, T. Delworth, R. J. Stouffer, M. Latif, B. McAvaney, and J. F. B. Mitchell, 2007: The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bull. Amer. Meteor. Soc.,* **88,** 1383–1394.

——, and Coauthors, 2009: Decadal prediction. *Bull. Amer. Meteor. Soc.,* **90,** 1467–1465.

Msadek, R., K. W. Dixon, T. L. Delworth, and W. Hurlin, 2010: Assessing the predictability of the Atlantic meridional overturning circulation and associated fingerprints. *Geophys. Res. Lett.,* **37,** L19608, doi:10.1029/2010GL044517.

Murphy, J., and Coauthors, 2010: Towards prediction of decadal climate variability and change. *Procedia Environ. Sci.,* **1,** 287–304, doi:10.1016/j.proenv.2010.09.018.

NRC, 2010: *Assessment of Interseasonal to Interannual Climate Prediction and Predictability.* National Academies Press, 182 pp.

Palmer, T. N., and Coauthors, 2004: Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction (DEMETER). *Bull. Amer. Meteor. Soc.,* **85,** 853–872.

Rayner, S., D. Lach, and H. Ingram, 2005: Weather forecasts are for wimps: Why water resource managers do not use climate forecasts. *Climatic Change,* **69,** 197–227.

Saha, S., and Coauthors, 2006: The NCEP Climate Forecast System. *J. Climate,* **19,** 3483–3517.

Shukla, J., R. Hagedorn, M. Miller, T. N. Palmer, B. Hoskins, J. Kinter, J. Marotzke, and J. Slingo, 2009: Revolution in climate prediction is both necessary and possible: A declaration at the World Modelling Summit for Climate Prediction. *Bull. Amer. Meteor. Soc.,* **90,** 175–178.

Smith, D., S. Cusack, A. Colman, A. Folland, G. Harris, and J. Murphy, 2007: Improved surface temperature prediction for the coming decade from a global circulation model. *Science,* **317,** 796–799.

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

Stockdale, T. N., and Coauthors, 2010: Understanding and predicting seasonal-to-interannual climate variability—The producer perspective.

Procedia Environ. Sci., **1,** 55–80, doi:10.1016/j.proenv.2010.09.006.

——, and Coauthors, 2011: ECMWF Seasonal Forecast System 3 and its prediction of sea surface temperature. *Climate Dyn.,* **37,** 455–471, doi:10.1007/s00382-010-0947-3.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2009: A summary of the CMIP5 experiment design. PCMDI Rep., 33 pp. [Available online at http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.]

van der Linden, P., and J. F. B. Mitchell, Eds., 2009: ENSEMBLES: Climate change and its impacts at seasonal, decadal and centennial timescales; Summary of research and results from the ENSEMBLES project.. Met Office Hadley Centre Rep., 160 pp. [Available online at http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdf.]

Vera, C., and Coauthors, 2010: Needs assessment for climate information on decadal timescales and longer. *Procedia Environ. Sci.,* **1,** 275–286, doi:10.1016/j.proenv.2010.09.017.

Vimont, D. J., D. S. Battisti, and A. C. Hirst, 2003: The seasonal footprinting mechanism in the CSIRO general circulation models. *J. Climate,* **16,** 2653–2667.

SKILL OF REAL-TIME SEASONAL ENSO MODEL PREDICTIONS DURING 2002–11

Is Our Capability Increasing?

BY ANTHONY G. BARNSTON, MICHAEL K. TIPPETT, MICHELLE L. L'HEUREUX, SHUHUA LI, AND DAVID G. DEWITT

The low predictability of the past decade masked a gradual improvement of ENSO predictions, with skill of dynamical models now exceeding that of statistical models.

During the last two to three decades, one might reasonably expect our ability to predict warm and cold episodes of the El Niño–Southern Oscillation (ENSO) at short and intermediate lead times to have gradually improved. Such improvement would be attributable to improved observing and analysis/assimilation systems, improved physical parameterizations, higher spatial resolution, and better understanding of the tropical oceanic and atmospheric processes underlying the ENSO phenomenon (e.g., Guilyardi et al. 2009).

Studies in the 1990s showed real-time ENSO prediction capability at a moderate level, with forecast versus observation correlations of about 0.6 for 6-month lead predictions (i.e., 6 months between the time of the forecast and the *beginning* of the predicted period) of 3-month mean conditions (Barnston et al. 1994). At that time, dynamical and statistical models showed comparable skills. The lack of conclusive ability for dynamical models to outperform statistical models was also found in predictions of the very strong El Niño of 1997/98 (Landsea and Knaff 2000; Barnston et al. 1999). Predictions at the 0.6 skill level are useful but leave much to be desired. The performance of statistical predictions was considered because they are simpler and less expensive to develop and serve as a baseline reference against which the skill of the more complex dynamical models can be compared.

Beginning early in 2002, predictions from a large number of models for the sea surface temperature (SST) in the Niño-3.4 region (5°N–5°S, 120°–170°W; Barnston et al. 1997) have been collected and displayed each month on a graph called the "ENSO prediction

AFFILIATIONS: BARNSTON, LI, AND DEWITT—International Research Institute for Climate and Society, The Earth Institute of Columbia University, Palisades, New York; TIPPETT— International Research Institute for Climate and Society, The Earth Institute of Columbia University, Palisades, New York, and Center of Excellence for Climate Change Research/Dept of Meteorology, King Abdulaziz University, Jeddah, Saudi Arabia; L'HEUREUX— National Oceanic and Atmospheric Administration, National Weather Service, Climate Prediction Center, Camp Springs, Maryland
CORRESPONDING AUTHOR: Anthony Barnston, International Research Institute for Climate and Society, 61 Route 9W, P. O. Box 1000, Columbia University, Palisades, NY 10964-8000.
E-mail: tonyb@iri.columbia.edu

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-11-00111.1

A supplement to this article is available online (10.1175/BAMS-D-11-00111.2)

In final form 30 November 2011

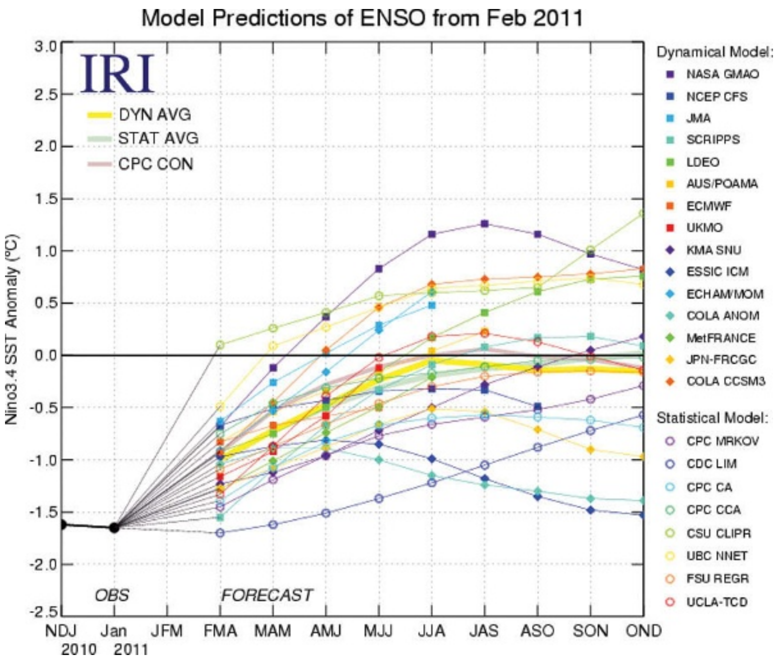


Fig. 1. Example of an ENSO prediction plume (from Feb 2011 just following the mature stage of a significant La Niña).

plume" (Fig. 1), on an International Research Institute for Climate and Society (IRI) web page (http://iri.columbia.edu/climate/ENSO/currentinfo/SST_table.html) and shown in the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center's (CPC's) monthly ENSO discussion. This paper reviews the performance of the constituent models and attempts to discern changes (ideally, improvements) from the levels seen in the earlier studies. We reexamine the question of the relative performance of dynamical and statistical models, and also compare the skills of 9 yr of real-time predictions to those of longer-term (30-yr) hindcasts from some of the same models, and discuss possible explanations for their differences.

An overview of the data, methods, and ENSO prediction models is provided in section 2. Results are shown and examined in section 3, and a discussion and some conclusions are given in section 4.

DATA, METHODS, AND MODELS. *Data.* The ENSO predictions issued each month from February 2002 through January 2011 are examined here for multiple lead times for future 3-month target (i.e., predicted) periods. The last target period is January–March 2011, while the earliest target period is February–April 2002 for the shortest lead time and October–December 2002 for the longest lead time.

The forecast data from a given model consist of a succession of running 3-month mean SST anomalies with respect to the climatological means for the respective predicted periods, averaged over the Niño-3.4 region. Predicted periods begin with the 3-month period beginning immediately after the latest available observed data, and continue for increasing lead times until the longest lead time provided by the given model, to a maximum of nine running 3-month periods. Here, lead time is defined by the number of months of separation between the latest available observed data and the beginning of the 3-month forecast target period. (For example, using observed data through March, a prediction for the April–June season has a lead time of 0 months, for May–July a lead of 1 month, etc.) Typically new predictions become available one to two weeks following the last available month of observed data, so that the 0-month lead prediction for the April–June season becomes available during mid-April.

Although anomalies were requested to be with respect to the 1971–2000 climatology, some prediction anomalies were with respect to means of other periods, such as from 1982 to the early 2000s for some dynamical predictions. No attempt was made to adjust for these discrepancies.[1] Similarly, although bias correction was encouraged (some centers conducted statistical corrections on their model output), no biases were corrected by the IRI, and the forecasts were used as disseminated by the producers. All of the dynamical models produce an ensemble of predictions, representing a probability distribution of outcomes. Although these distributions can be verified probabilistically, here we only consider the ensemble mean as a deterministic prediction. This approach enables the dynamical models to be verified in the same way as the statistical models, most of which provide only a single prediction.[2]

The Reynolds–Smith (Reynolds et al. 2002) version 2 optimal interpolation (OI) observed SST

[1] A warming trend in the Niño-3.4 region has been negligible within the 1981–2011 period, using the OI SST data (Reynolds et al. 2002), although the 1970s were about 0.4° cooler than the 1981–2011 average.

[2] The CPC CA is an example of a statistical model that produces an ensemble of predictions.

data averaged over the Niño-3.4 region is used to verify the model ENSO predictions. The OI SST has a base period of late 1981 to present, and the 1981–2010 period is used here to define the verification anomalies.

Methods. The verifications conducted here focus on the performance of individual models, rather than on multimodel mean predictions as examined in Tippett et al. (2012). Accordingly, detection of skill differences between dynamical and statistical models is carried out through aggregating the skills (as opposed to the predictions) of the models of each type. Verifications are applied to real-time predictions over the 9-yr period, as well as to longer-term hindcasts of some of the models, to compare the performance between the two settings and two base periods.

Verification measures used include the temporal correlation, root mean squared error, bias, and standard deviation ratio. Applied to each of the several lead times, the measures are used both for all predictions over the 9-yr period and for seasonally stratified predictions. An additional diagnostic is the lag correlation between forecasts and observations, to detect systematic tendencies for predictions intended for a given lead time to verify with higher skill at other lead times. This diagnostic will reveal a tendency of most models to be late in forecasting ENSO state transitions, such that predictions verify better on the observations at lead times earlier than those intended.

The ENSO prediction models. The 20 models whose real-time predictions are evaluated here include 12 dynamical models and 8 statistical models, as shown in Table 1.[3] The statistical models are developed using historical datasets and include various forms of regression (some based on autocorrelations or transition statistics), neurological networks, or analogues. The dynamical models, based primarily on the physical equations of the ocean–atmosphere system, range from relatively simple and abbreviated physics to comprehensive fully coupled or anomaly coupled models. Some models were introduced during the course of the study period, or replaced a predecessor model. Many of the dynamical models have been upgraded throughout the study period, while the statistical models have remained more constant. The model names used here refer to the model versions in early 2011. A brief guide to each of the models, with key references, is provided in the appendix (available online at http://dx.doi.org/0.1175/BAMS-D-11-00111.2).

RESULTS. *ENSO variability during the 2002–11 period.* The 9-yr study period is too short for many findings to be statistically robust, but long enough for some results to be suggestive and warrant further exploration. Substantial sampling errors for a 9-yr period are expected for both model behavior and observed ENSO behavior. To assess qualitatively whether the ENSO variability during the 9-yr study period is approximately comparable to that of a multidecadal period, features of the time series of observed seasonal Niño-3.4 SST anomalies during 2002–11 are compared with those of 1981–2011 (Fig. 2). During 2002–11, at least moderate strength El Niño events occurred in 2002/03 and 2009/10, and likewise for

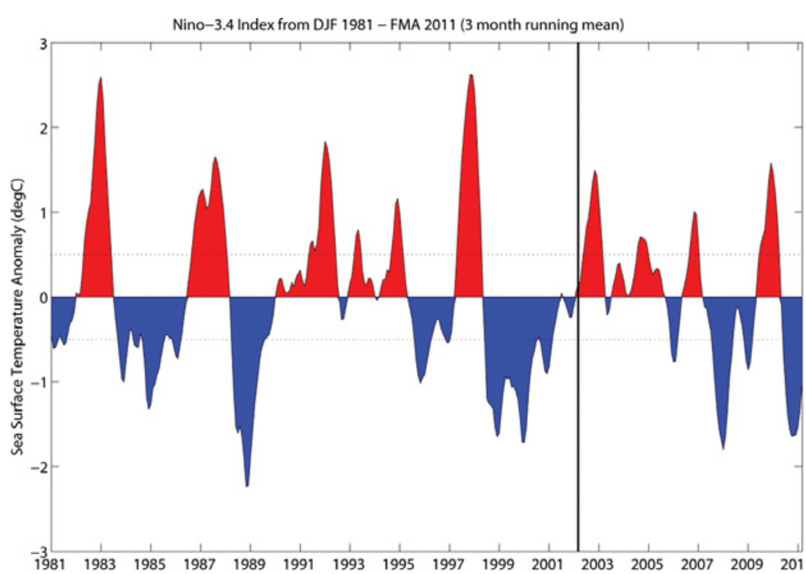


Fig. 2. Time series of running 3-month mean SST anomaly with respect to the 1981–2010 period climatology in the Niño-3.4 region for 1981–2011, highlighting the 2002–11 study period.

[3] Three dynamical models currently included on the plume that do not have sufficient time history on the plume to be evaluated in most of the analyses here are the Japan Frontier coupled model (Luo et al. 2005), the Météo-France coupled model (Déqué et al. 1994; Gibelin and Déqué 2003), and the COLA CCSM3 coupled model (Kirtman and Min 2009).

Table 1. Dynamical and statistical models whose forecasts for Niño-3.4 SST anomaly are included in this study. Note that some models were introduced during the course of the study period, or replaced a predecessor model.

Dynamical models	Model type
NASA GMAO	Fully coupled
NCEP CFS (version 1)	Fully coupled
Japan Meteorological Agency	Fully coupled
Scripps Hybrid Coupled Model (HCM)	Comprehensive ocean, statistical atmosphere
Lamont–Doherty	Intermediate coupled
Australia POAMA	Fully coupled
ECMWF	Fully coupled
UKMO	Fully coupled
Korea Met. Agency SNU	Intermediate coupled
Univ. Maryland ESSIC	Intermediate coupled
IRI ECHAM/MOM	Fully coupled, anomaly coupled
COLA Anomaly	Anomaly coupled
COLA CCSM3	Fully coupled
Météo-France	Fully coupled
Japan Frontier FRCGC	Fully coupled
Statistical Models	**Method and predictors**
NOAA/NCEP/CPC Markov	Markov: Preferred persistence and transitions in SST and sea level height fields
NOAA/ESRL Linear Inverse Model (LIM)	Refined POP: Preferred persistence and transitions within SST field; optimal growth structures
NOAA/NCEP/CPC Constructed Analogue (CA)	Analogue-construction of current global SSTs
NOAA/NCEP/CPC Canonical Correlation Analysis (CCA)	Uses SLP, tropical Pacific SST and subsurface temperature (subsurface not used beginning in 2010)
NOAA/AOML CLIPER	Multiple regression from tropical Pacific SSTs
UBC Neural Network (NN)	Uses sea level pressure and Pacific SST
Florida State Univ. multiple regression	Uses tropical Pacific SST, heat content, winds
UCLA TDC multilevel regression	Uses 60°N–30°S Pacific SST field

La Niña events in 2007/08 and 2010/11. Weaker El Niño events occurred in 2004/05 and 2006/07, and borderline La Niña events[4] occurred in 2005/06 and 2008/09. The Northern Hemisphere autumn/winter of 2003/04 was the only peak ENSO season having neutral ENSO conditions.

Table 2 shows the seasonal march of observed interannual standard deviation of Niño-3.4 SST for the 1981–2011 period compared with the 2002–11 study period, and the mean anomaly of the study period. The two profiles are fairly similar, with the study period showing somewhat lower variability, particularly during the middle of the calendar year. This smaller variability is likely related to the lack of very strong events such as the El Niño events of 1982/83 and 1997/98. A lack of a substantial upward trend within the 1981–2011 period is noted in Fig. 2, so that the higher standard deviation of the longer period cannot be attributed to a trend. The mean anomaly of the study period compared with the 1981–2010 period is weakly negative (positive) in the first (second) half of the calendar year (Table 2). A chi-square test indicates that the difference in standard deviation between 2002–11 and 1981–2011 is not statistically

[4] These two events fell slightly short of the criteria used by the Climate Prediction Center to qualify as a nonneutral ENSO episode (Kousky and Higgins 2007), but 2008/09 qualifies using the 1981–2010 climatology for the OI SST data used here.

Table 2. Seasonal march of interannual mean anomaly and standard deviation (°C) of Niño-3.4 SST for the 2002–11 study period, and the standard deviation of the longer 1981–2011 period.

Season	1981–2011 SD	2002–11 Mean SD
DJF	1.21	−0.10 1.10
JFM	1.03	−0.15 0.88
FMA	0.81	−0.07 0.62
MAM	0.65	−0.04 0.39
AMJ	0.59	−0.01 0.31
MJJ	0.64	0.04 0.40
JJA	0.74	0.09 0.53
JAS	0.80	0.09 0.69
ASO	0.91	0.09 0.84
SON	1.04	0.10 0.99
OND	1.20	0.11 1.12
NDJ	1.26	0.03 1.18

significant, with the strongest two-sided p value at 0.15 for the April–June season. Figure 3 shows autocorrelation of Niño-3.4 SST as a function of lead time and target season for the 1981–2011 period compared with the 2002–11 study period. The 2002–11 period has higher autocorrelation than the 1981–2011 period at short and intermediate lag times for target periods near the end and very beginning of the calendar year, indicating a persistence of SST anomalies during the time of year of typical ENSO event maturity. This may be related to the high proportion of the years between 2002 and 2011 having nonneutral ENSO conditions. On the other hand, autocorrelations are more strongly negative during 2002–11 than 1981–2011 at long lead for periods traversing the April–June period, consistent with an enhanced biennial variability during the study period. In fact, alternations of phase between northern autumn/early winter of consecutive years occurred in five of the eight year-to-year transitions, while a continuation of the same sign of anomaly occurred in three transitions. Using the 1981–2011 autocorrelations as population values and applying a Fisher Z test of the difference between them and the corresponding 9-yr autocorrelations, none of the latter are outside of the 95% confidence interval about the longer period values. Hence, the visible differences in the profiles of the two periods may be attributed to the expected sampling variability of a 9-yr period.

Whether the autocorrelation structure of the 2002–11 test period renders it more or less predictable than a period with a structure like that of 1981–2011 is an open question. It will be shown below, however, that the lower variability of the 9-yr period reduces its predictability.

Real-time predictive skills of individual models. Time series of the running 3-month mean observed SST anomalies in the Niño-3.4 region and the corresponding predictions by 23 prediction models at 0-, 2-, 4- and 6-month lead times are shown in Fig. 4. Figure 4 shows that the models generally predicted the variations of ENSO with considerable skill at short lead times, and decreasing skill levels with increasing lead times. A feature seen in Fig. 4 is a tendency for most of the models to predict the continuation of SST anomalies beyond their observed periods, and to do so to a greater extent for longer lead times (shown by color shading that tilts to the right with increasing lead time). False alarms have also occurred (e.g., some models predicted La Niña for 2003/04, which did not happen) but these have been less common than prolonged anomaly persistence. Figure 4 indicates forecast differences among the models that

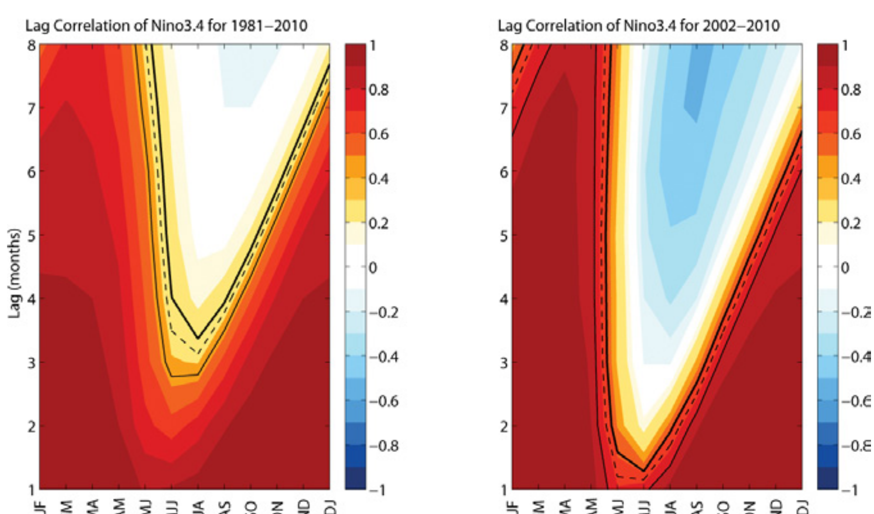


Fig. 3. Autocorrelation of Niño-3.4 SST as a function of lead time and target season for (left) the 1981–2011 period and (right) the 2002–11 study period. Contours show 90%, 95%, and 99% two-sided significance levels for positive autocorrelation for each of the record lengths.

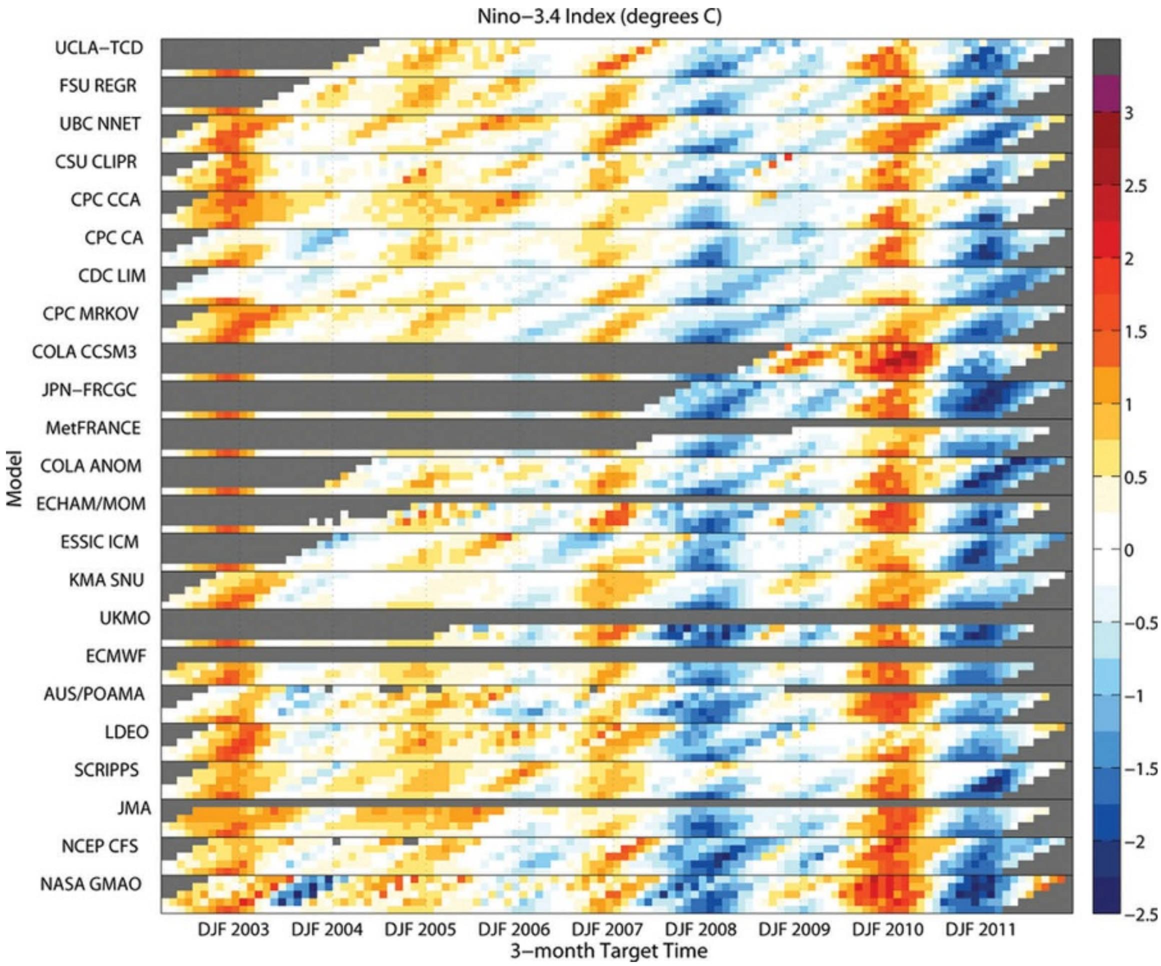


Fig. 4. Time series of running 3-month mean Nino-3.4 SST observations (°C anomaly), and corresponding model predictions for the same 3-month period from earlier start times at 0-, 2-, 4-, and 6-month leads. Data for each model are separated by thin black horizontal lines. The first eight models at the top are statistical models. For each model, the bottom row shows the observations, and the four rows above that row show predictions at the four increasing lead times. Vertical dotted lines demarcate calendar years, separating Nov–Jan from Dec–Feb. Observations span from Feb–Apr 2002 to Jan–Mar 2011, while forecasts at longer lead times start and end with later seasons. Gray shading indicates missing data.

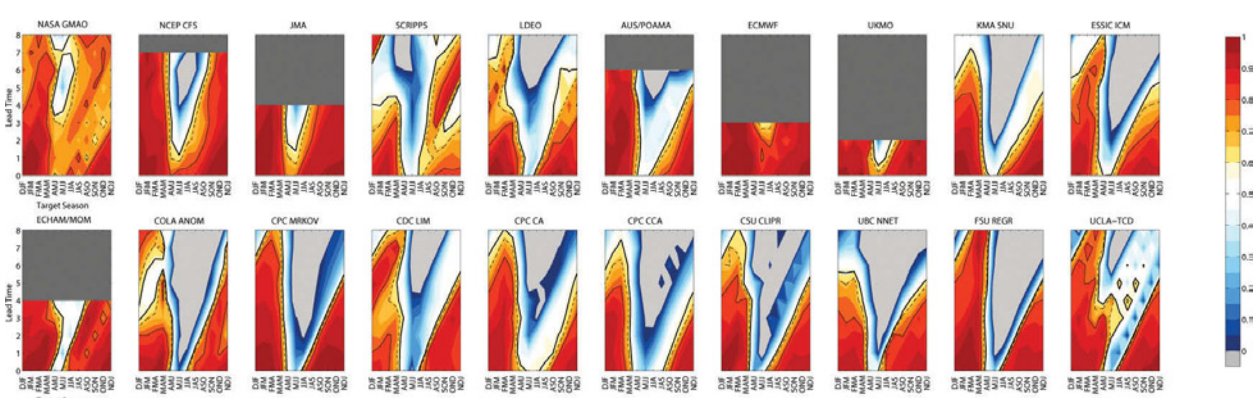


Fig. 5. Temporal correlation between model forecasts and observations as a function of target season and lead time. Each panel highlights one model. The first 12 models are dynamical, followed by 8 statistical models. The thick solid contour shows the 90% significance level, the dashed contour the 95% level, and the thin solid contour the 99% level.

become increasingly pronounced with increasing lead time. These differences raise the question of whether some models are systematically more skillful than others.

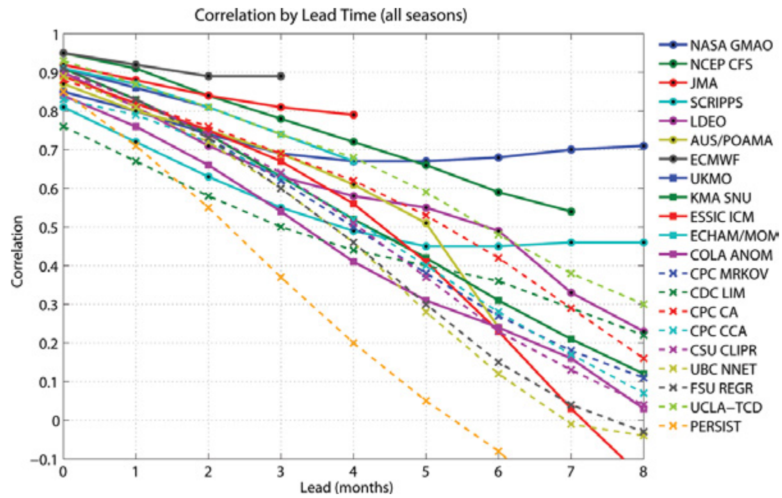


Fig. 6. Temporal correlation between model forecasts and observations for all seasons combined, as a function of lead time. Each line highlights one model. The eight statistical models and the persistence model are shown with dashed lines and the cross symbol.

Correlation and root mean squared error. Figure 5 shows the temporal correlation between model predictions and the corresponding observations as a function of target season and lead time, with a separate panel for each model. The correlation skill patterns of the models appear roughly comparable. All indicate a northern spring predictability barrier, with short lead prediction skills having a relative minimum for northern summer, extending to later seasons at longer lead times. Relative to the statistical models, Fig. 5 shows higher correlation skills by many of the dynamical models for seasons in the middle of the calendar year that generally have lowest skill. By contrast, for seasons having highest skills (e.g. northern winter target seasons at short to moderate lead times), skill differences among models and between model types appear small.

Figure 6 shows individual model correlation skills as a function of lead time for all seasons combined, while the top and bottom panels of Fig. 7 show skills for the pooled target seasons of NDJ,[5] DJF, and JFM, and for MJJ, JJA, and JAS, respectively. Overall, model correlation skills at

[5] Seasons are named using the first letters of the three constituent months (e.g., DJF refers to December–February).

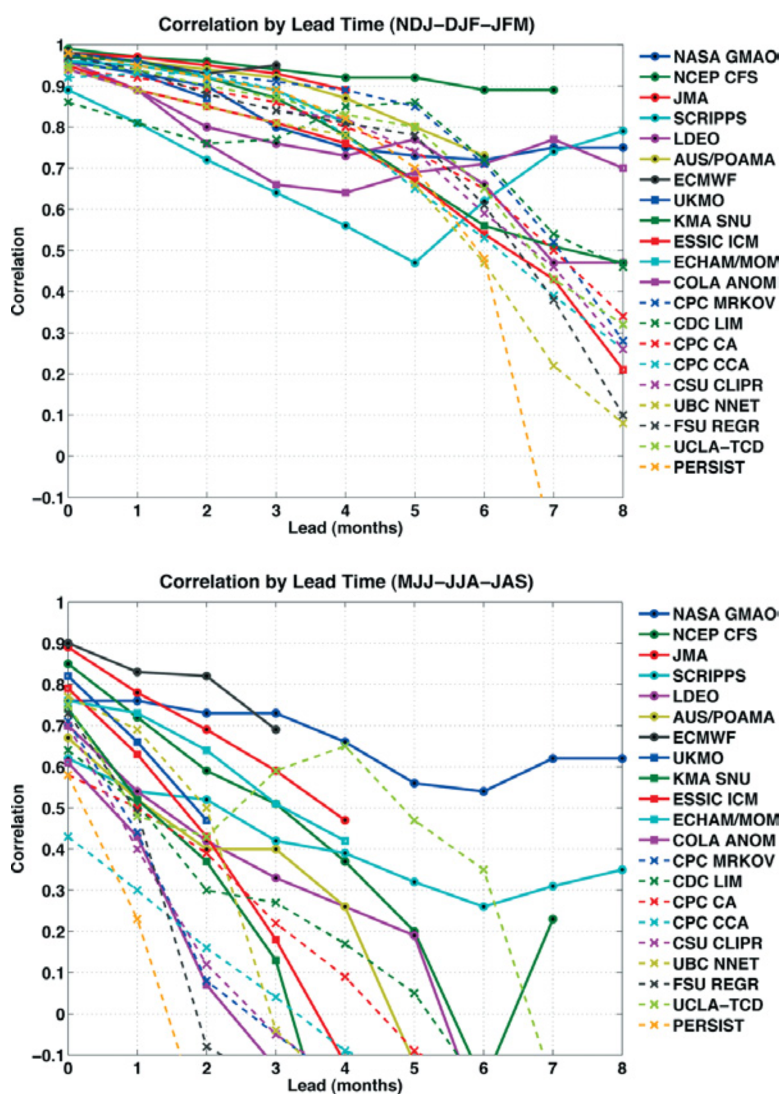


Fig. 7. (top) Temporal correlation between model forecasts and observations for Nov–Jan, Dec–Feb, and Jan–Mar as a function of lead time. Each line highlights one model. The eight statistical models and the persistence model are shown with dashed lines and the cross symbol. (bottom) As at top, but for May–Jul, Jun–Aug, and Jul–Sep.

Table 3. 90% and 95% confidence intervals for correlation coefficients for sample sizes of 9 and 30, for bivariate normal population distributions. Because of symmetry, only zero or positive population correlation values are shown.

Sampling variability for *n* = 9					Sampling variability for *n* = 30				
Lower 2.5%	Lower 5%	**Popul correl**	Upper 5%	Upper 2.5%	Lower 2.5%	Lower 5%	**Popul correl**	Upper 5%	Upper 2.5%
−0.66	−0.59	**0.0**	0.59	0.66	−0.36	−0.31	**0.0**	0.31	0.36
−0.45	−0.35	**0.3**	0.75	0.80	−0.07	−0.01	**0.3**	0.55	0.60
−0.11	0.20	**0.6**	0.88	0.90	0.31	0.36	**0.6**	0.77	0.79
0.29	0.40	**0.8**	0.94	0.96	0.62	0.65	**0.8**	0.89	0.90
0.59	0.66	**0.9**	0.97	0.98	0.80	0.82	**0.9**	0.95	0.95

6-month lead range anywhere from 0.1 to about 0.7 for all seasons combined, while predictions for the northern winter season range from 0.5 to 0.9, and for the northern summer season from below zero to 0.55. Overall, for lead times greater than 2 months, persistence forecasts have lower correlation than that of any of the models. However, although the northern winter season is considerably better predicted than summer, a clear improvement in skill of the models over that of persistence is not seen for winter until leads of 6 months or more, while for summer persistence is the worst prediction for leads of 1 month or more. The model skill levels for all seasons combined (Fig. 6) differ from one another noticeably at all lead times, and some models that fare well (or poorly) at short lead times change their relative standing at intermediate or long lead times (e.g., Scripps). Averaged over all seasons, skills average somewhat lower than the 0.6 level found at 6-month lead in earlier studies (e.g., Barnston et al. 1994). However, a small number of current models, some of which do not predict out to 6 months lead, have shorter-lead skill levels that would exceed a 0.6 correlation if their forecast range were extended, *and* if their skill followed a downward slope with increasing lead time averaging that shown by other models having longer maximum lead times. Examples of models with such good or potentially good skill include those of the European Centre for Medium-Range Weather Forecasts (ECMWF), the National Aeronautics and Space Administration Global Modeling and Assimilation Office (NASA GMAO), and the Japan Meteorological Agency (JMA); the National Centers for Environmental Prediction Climate Forecast System (NCEP CFS; version 1) skill approximately equals 0.6. However, two caveats in the comparison of skills of today's models against models of 10–20 years ago are that 1) the ENSO variability during the 2002–11 period will be demonstrated to have been more difficult to predict than that over 1981–2011 in general and 2) the current set of predictions were made in real time, while those examined in previous studies were partly hindcasts. Both factors will be examined further below.

One reasonably might ask whether the skill differences at any lead time are sufficient, for a 9-yr period, to statistically distinguish among the performance

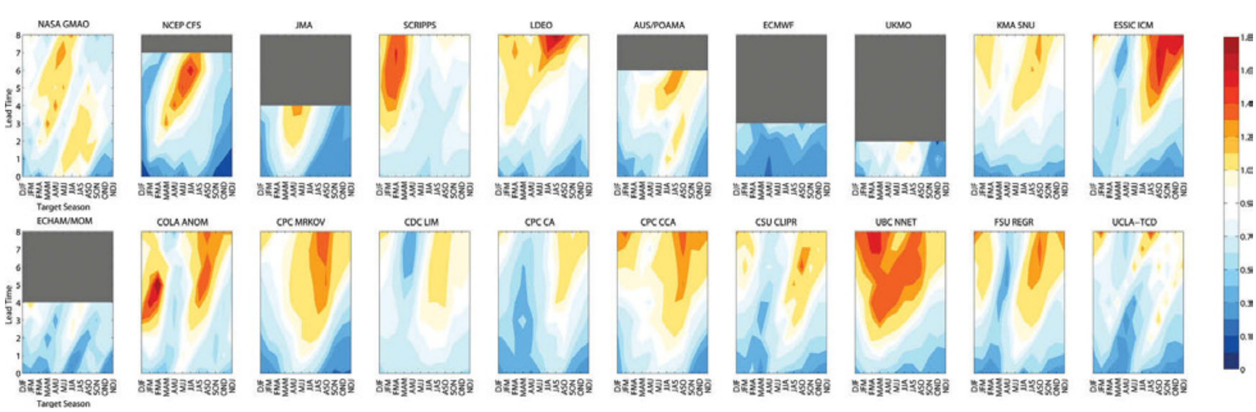


Fig. 8. RMSE in standardized units, as a function of target season and lead time, with a separate panel for each model. The first 12 models are dynamical, followed by 8 statistical models.

levels of some of the models. The expected sampling error of a correlation coefficient is shown in Table 3 as 90% and 95% confidence intervals about several population correlations, for a sample size (n) of 9 and 30. For $n = 9$ and a population correlation of 0.8, for example, the 90% confidence interval ranges from 0.40 to 0.94—a wide interval. For skills derived from all seasons combined, the effective sample may be somewhat larger than 9 but will be far smaller than 108 because of the high month-to-month autocorrelation of the observed and modeled ENSO state (Fig. 3), given the typical lifetime of ENSO episodes of 7–11 months. The determination of statistically significant differences between skills of any pair of individual models is not a main goal of this study. However, the statistical significance of skill differences between dynamical and statistical model types *is* of interest, and is addressed below.

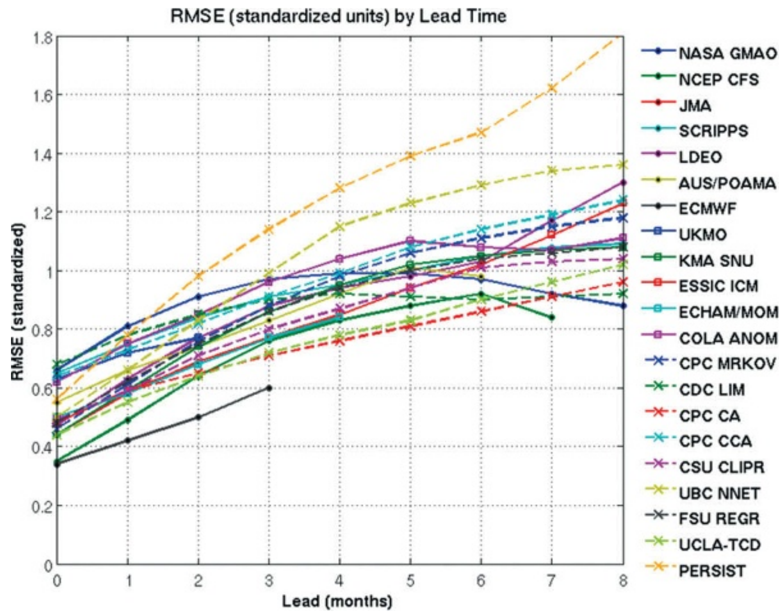


Fig. 9. RMSE in standardized units, as a function of lead time for all seasons combined. Each line highlights one model. The eight statistical models and the persistence model are shown with dashed lines and the cross symbol.

The correlation between model predictions and observations reflects purely the discrimination ability of the models, since biases of various types do not affect this metric. However, such prediction biases (e.g., calibration problems involving the mean or the amplitude of the predictions) are also part of overall forecast quality, despite being correctable in many cases. To assess performance in terms of both calibration and discrimination, root mean square error (RMSE) is examined. Here the RMSE is standardized for each season individually, to scale RMSE so that climatology forecasts (zero anomaly) result in the same RMSE-based skill (of zero) for all seasons, and all seasons' RMSE contribute equally to a seasonally combined RMSE. Figure 8 shows RMSE as a function of target season and lead time, with a separate panel for each model, and Fig. 9 shows RMSE as a function of lead time for all seasons together. The ECMWF model has the lowest RMSE over its range of lead times. For lead times greater than 2 months, persistence forecasts have higher RMSE than that of any of the models. There is clearly some comparability between correlation skill (Fig. 5) and RMSE (Fig. 8), with models having highest correlation tending to have low RMSE. However, exceptions are discernible, due to the effects of mean biases and amplitude biases.

Mean bias and standard deviation ratio. Toward examining specific calibration-related diagnostics individually, Fig. 10 shows model mean bias for each model, defined as the mean of the model prediction minus the mean of the observation, as a function of target season and lead time.

The seasonal patterns of mean bias (Fig. 10) indicate a common pattern of positive bias near the beginning of the calendar year at short lead times, migrating to later seasons with increasing lead time. Inspection of the individual time series indicates that this bias is related to the generally unpredicted early dissipation of the El Niño events of 2002/03 and 2006/07, underprediction of the northern winter peaks of the La Niña events of 2007/08 and 2008/09, and the failure to predict the late-emerging borderline La Niña events of 2005/06 and 2008/09 in northern autumn. The bias near the beginning of the calendar year can be attributed more generally to failure to predict exceptions to the typical tendency of persistence of the ENSO state between approximately October and February.

On the other hand, a tendency for negative bias is noted near the middle of the calendar year at short lead times, migrating to later seasons for longer leads. This bias can be traced to underprediction of the El Niños of 2002/03, 2006/07, and 2009/10 during their initial rapid growth phase during northern summer. Although underprediction of the La Niña

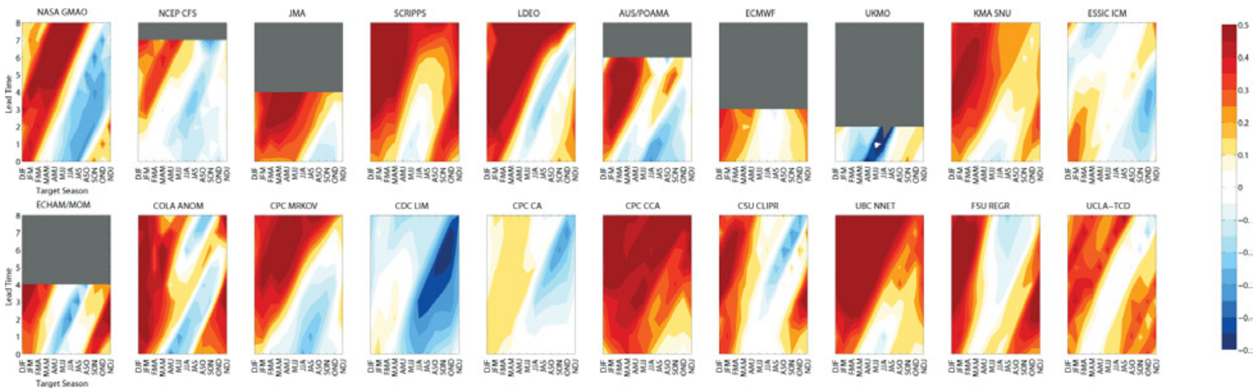


Fig. 10. Mean bias as a function of target season and lead time, with a separate panel for each model. The first 12 models are dynamical, followed by 8 statistical models.

events is similarly noted, there were slightly more El Niño than La Niña episodes during the period. The tendency for reversal from positive to negative model bias from the beginning to the middle of the calendar year at short lead times is consistent with the models being slow to develop any ENSO event during late northern spring and summer, and also late to end any event near the beginning of the calendar year, combined with the slight ENSO asymmetry favoring El Niño during the study period.

Figure 11 shows, for each model, the ratio of the interannual standard deviation of model predictions to that of the observations, as a function of target season and lead time. First, let us consider what the optimal values of this ratio are. Ideally, an ensemble mean, or for that matter a regression forecast, is a representation of the predictable signal. Ensemble averaging directly (and regression indirectly) removes unpredictable noise. Observations, on the other hand, contain both signal and noise. Therefore, the ratio of ensemble mean variance to observation variance is the ratio of signal variance to total variance (signal plus noise). In other words, the optimal value of the ratio of ensemble mean variance to observation variance is the fraction of explained variance, which is the square of the correlation coefficient. Ideally, then, the ratio of ensemble mean standard deviation to observation standard deviation should always be less than 1, and should be much less than 1 when skill is low. The signal versus noise basis for ensemble mean variance is discussed in Rowell (1998), and for regression-based statistical prediction variance in Hayes (1973). Thus, the standard deviation ratios shown in Fig. 11 should ideally look similar to the plots of correlation skill shown in Fig. 5. This is clearly not the case; the ratio is not bounded by 1 and does not decrease with lead time. In fact, the models tend to have standard deviation ratios that maximize near the time of year when skills are lowest. Although a 9-yr period is inadequate to establish robust estimates of correlation skills from which to derive the optimum prediction-to-observation standard deviation ratio, it is obvious that many of today's models have serious challenges reproducing realistic signal-to-noise ratios.

Examples of the contributions of mean bias and amplitude bias to RMSE in individual models can be identified. The NASA GMAO coupled model is one of the higher scoring models for correlation skill at lead times of 3 or more months, and the highest at long lead (Figs. 6 and 7). However, its RMSE is less favorable at intermediate (3–5 months) lead times (Figs. 8 and 9) because the model's good discrimination is offset by a substantially inflated amplitude at short to intermediate lead times, particularly just before the middle of the calendar year (Fig. 11) when the observations have smallest interannual variability and predictive skill is lowest. A seasonal pattern of mean bias (Fig. 10), also present in NASA GMAO, is not severe relative to that of other models. The NCEP CFS (version 1) model has a high correlation skill, and it is relatively free of bias.[6] While its RMSE is also generally favorable, it is somewhat degraded at long lead times because the standard deviation ratio is too high just before the middle of the calendar year at intermediate and long leads (Fig. 11). The JMA model is one of the best performers in correlation and RMSE, hindered to some extent by mean bias in the early part of the year and too high a standard deviation ratio for the northern spring seasons. The ECMWF model shows exemplary performance in terms of correlation, mean bias, and a standard deviation ratio that is too high only for the MAM and AMJ seasons. Although

[6] Since 2009, NCEP has applied a statistical correction to its Niño-3.4 SST predictions.

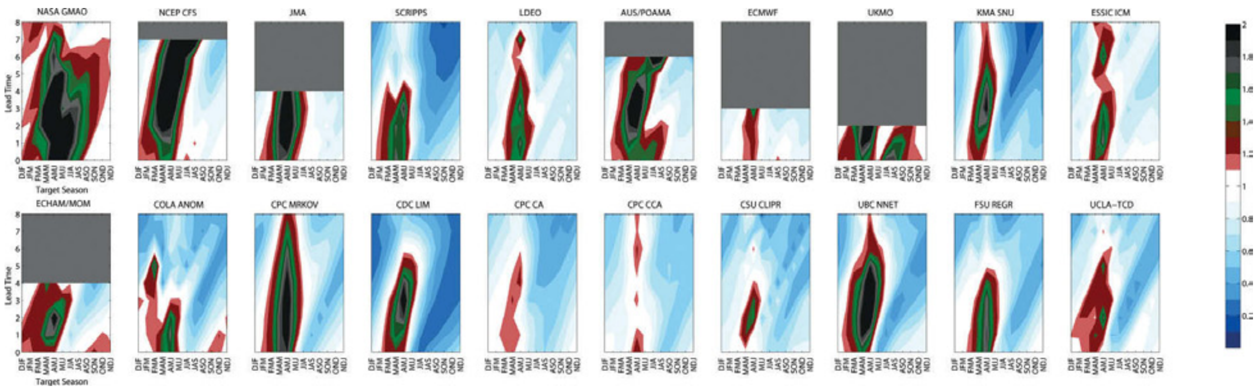


Fig. 11. Interannual standard deviation ratio of model predictions to observations as a function of target season and lead time, with a separate panel for each model. The first 12 models are dynamical, followed by 8 statistical models.

it does not predict to long lead times,[7] its RMSE is the lowest among all models in the study, particularly near the middle of the calendar year (Fig. 8) when prediction is most difficult (Stockdale et al. 2011).

Statistical models are typically designed to minimize RMSE and have little, if any, mean or amplitude bias in the training sample (but may have biases in independent predictions, particularly when they are temporally distant from the training period and a trend exists). The CPC canonical correlation analysis (CCA) model has relatively weak correlation skill at short lead times, other than near the very beginning and end of the calendar year; this weakness, combined with a strong positive bias during the first half of the calendar year, produces a comparatively high RMSE at short lead times despite a mainly favorable standard deviation ratio. The CPC constructed analog (CA) model has lower RMSE than that of most models because of slightly above-average correlation skill (Figs. 5 and 6) and remarkably little mean bias (Fig. 10) or amplitude bias. The University of California at Los Angeles (UCLA) *Theoretical Climate Dynamics* (TCD) model has similar performance attributes, and has the highest seasonally combined correlation skill among the statistical models (Fig. 6), exceeded by only a few dynamical models.

The examples above are only a subset of what could be an exhaustive consideration of the performance attributes of the 20 ENSO prediction models over the study period.

Target period slippage. The rightward tilting of the color shading in the forecasts shown in Fig. 4 indicates that predictions correspond best with observations occurring earlier than the intended target season, particularly at intermediate and longer lead times. To capture this feature more clearly, Fig. 12 shows the correlation skills of each model as a function of lead time over a range of lag times, for all target seasons combined. The correlations at zero lag time reflect the skill of the predictions for the intended target period, while those at negative lag times show skills for target periods earlier than intended. Some degree of such "slippage" is noted for most of the models; this slippage tends to increase with increasing lead time. Marked slippage is noted for some of the statistical models, such as CPC Markov, the Climate Diagnostics Center linear inverse model (CDC LIM), the University of British Columbia neurological network model (UBC NNET), and The Florida State University regression model (FSU REGR). Two of the statistical models, UCLA TCD and CPC CA, lack substantial slippage. Dynamical models are not immune to slippage, as seen for example in the NCEP CFS (noted also in Wang et al. 2010), the Center for Ocean–Land–Atmosphere (COLA) anomaly model, and a few others. However, many of the models that exhibit relatively mild slippage are dynamical, such as ECMWF, NASA GMAO, the Met Office (UKMO), JMA, and the Lamont–Doherty intermediate coupled model (LDEO), although some of these models only forecast out to intermediate leads, precluding potentially larger slippage. Examination indicates that slippage has a common pattern of seasonal variation, being most pronounced for target periods in the middle of the calendar year and expanding to later seasons with increasing lead time (not

[7] The ECMWF predictions examined here were actually initialized one month earlier than were many of the other models, because the publicly available predictions are not updated until the middle of the month in order that the latest version may be sold commercially. This implies that the forecasts are of even greater quality than shown here.

shown). Slippage often presents itself when an El Niño or La Niña begins growing but is underpredicted (or predicted to grow later than observed) until it becomes at least moderately strong in the initial observations near the end of northern summer. Similarly, some models are systematically late in ending an ENSO event, creating a slippage effect in the first or second quarter of the calendar year by prolonging the event. Target period slippage can be described as an exaggerated tendency toward persistence, and therefore toward insufficient and/or late forecast signal evolution. As a systematic error, slippage can benefit from statistical correction (see Tippett et al. 2012).

Comparison of skill among models, and between dynamical and statistical models. Case-to-case discrimination (as indicated by correlation skill; Murphy 1988) is often considered the most important component of final skill, since many calibration (bias-related) problems are correctable, while discrimination reflects a more fundamental ability of the prediction model. Figure 13 shows the anomaly of the squared correlation between the model predictions and the observations with respect to the mean of the squared correlation over all 20 models[8] as a function of lead time and target season. Highlighted are some of the typical patterns of model differences, and patterns common to statistical or dynamical models collectively. With several exceptions, positive squared correlation anomalies are more commonly seen in the dynamical than statistical models, particularly in the comprehensive coupled dynamical models

[8] After squaring negative correlations, the negative sign is reinserted.

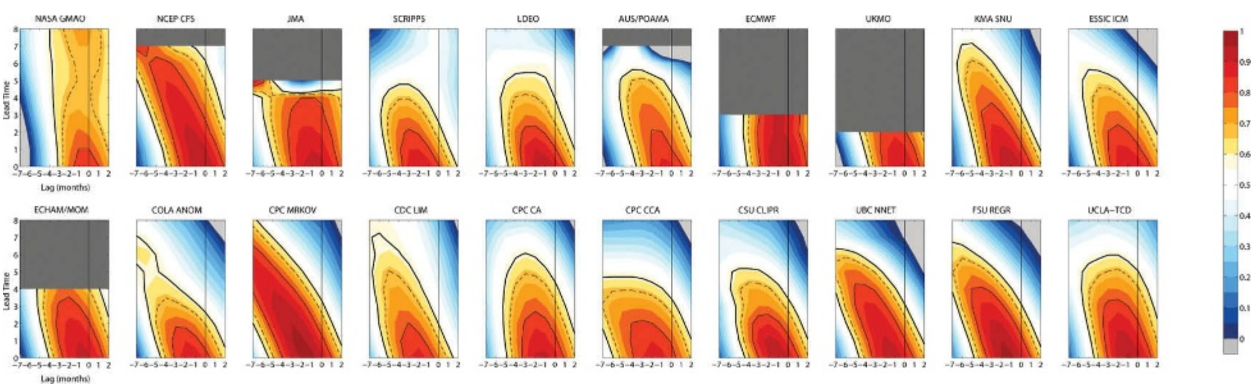


Fig. 12. Temporal correlation between model predictions and observations as a function of lag time and lead time for all seasons combined. A lag time of zero (denoted by the vertical line) shows the correlation between the forecast and observations for the intended target season, while negative lags show correlations between forecasts and observations occurring earlier than intended. A separate panel is shown for each model. The first 12 models are dynamical, followed by 8 statistical models. The thick solid contour shows the 90% significance level, the dashed contour the 95% level, and the thin solid contour the 99% level.

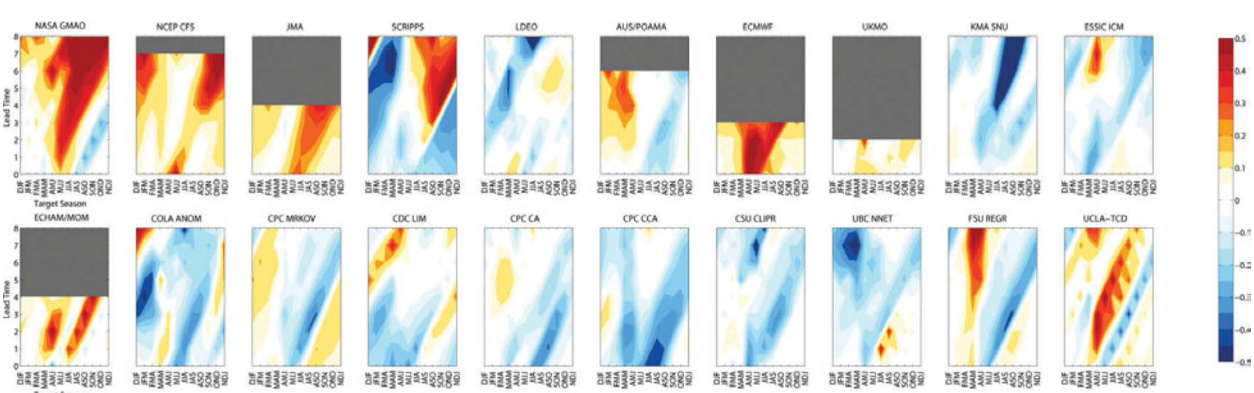


Fig. 13. Squared correlation anomaly (preserving negative sign) with respect to the mean of the squared correlation over all models for a given target season and lead time. The first 12 models are dynamical, followed by 8 statistical models.

(e.g., NASA GMAO, NCEP CFS, JMA, ECHAM/MOM, and particularly ECMWF). A typical specific weakness of many of the statistical models is their short lead predictions for the northern summer target seasons, extending to later seasons for longer lead predictions. These target periods involve the northern spring predictability barrier, a longstanding difficulty in ENSO prediction (e.g., Jin et al. 2008). Predictions whose lead times do not traverse the months of April to June, by contrast, appear more equally successful among all models. Such predictions, focusing largely on continuing the evolution of ENSO events already in progress, are enhanced most noticeably by good calibration, including an accounting of ENSO's observed seasonal phase locking (e.g., Zaliapin and Ghil 2010). Statistical models have historically performed well for ENSO predictions that escape the need to predict new ENSO evolution or phase transitions associated with the northern spring predictability barrier.

Establishing statistical significance of skill differences between dynamical and statistical models for specific times of the year is difficult for a 9-yr study period. However, while there is only a small time sample, the fairly large number of models can be used to help overcome the short period length if we accept this 9-yr study period as a fixed condition.

Models are ranked by correlation skill for each season and lead time separately, using the 9-yr sample. Systematic differences in the ranks of the dynamical and statistical models are identified using the Wilcoxon rank sum test. Additionally, the average correlation of the dynamical and statistical models is compared using a standard t test, applied to the Fisher Z equivalents of the correlations. The p values resulting from these two statistical approaches are shown in Table 4.

Table 4. Statistical significance results (two-sided p values), by target season and lead time, for differences in temporal correlation skill of dynamical versus statistical models: (top) Wilcoxon rank sum test for correlation skills, and (bottom) t test of difference in means of Fisher Z equivalents of the correlations skills. Entries statistically significant at the 0.05 level are shown in bold. Negative sign indicates cases when statistical models have higher ranks (or means) than dynamical models. The p values are shown to 3 decimal places when $p < 0.005$; 0.000 indicates p value <0.0005.

Wilcoxon rank sum test (field significance $p = 0.034$)

Lead	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	All
0	0.32	0.19	0.76	0.28	**0.01**	**0.01**	0.09	0.95	0.22	0.41	0.95	0.76	0.70
1	0.88	0.25	0.22	0.32	0.06	**0.003**	**0.02**	0.17	−0.68	0.34	0.68	1.00	0.64
2	1.00	0.76	0.32	0.19	0.17	**0.04**	**0.01**	**0.01**	0.54	−0.73	0.38	0.94	0.22
3	1.00	−0.93	0.32	0.14	0.36	0.19	0.14	**0.01**	**0.01**	0.25	1.00	−0.74	0.12
4	−0.33	−0.37	0.79	0.29	0.48	0.48	0.18	0.25	**0.01**	**0.004**	0.36	−0.21	0.16
5	−0.09	−0.29	−0.40	0.67	0.92	0.60	0.67	0.30	0.34	**0.03**	**0.002**	0.92	0.21
6	0.60	−0.60	−0.75	1.00	0.40	0.46	0.75	−0.83	0.75	0.46	**0.05**	**0.05**	0.25
7	**0.02**	1.00	−0.35	1.00	−0.64	0.20	0.82	0.91	0.70	0.73	0.25	**0.03**	0.35
8	**0.05**	**0.02**	1.00	−0.52	−0.44	1.00	0.19	−0.61	−0.66	−0.88	1.00	**0.05**	0.61

t test for mean difference (field significance $p = 0.026$)

Lead	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	All
0	0.27	0.19	0.65	0.22	**0.003**	**0.001**	0.06	0.48	0.41	0.65	0.74	0.46	0.49
1	0.50	0.37	0.12	0.16	**0.04**	**0.000**	**0.01**	0.10	−1.00	0.32	0.73	−0.85	0.29
2	−0.90	0.54	0.33	0.06	0.23	**0.04**	**0.001**	**0.01**	0.16	−0.86	0.29	0.93	0.12
3	−0.98	0.65	0.13	0.13	0.71	0.20	0.07	**0.002**	**0.001**	0.11	−0.90	−0.65	0.09
4	−0.35	−0.39	0.82	0.40	0.26	0.78	0.29	0.12	**0.002**	**0.000**	0.22	−0.19	0.11
5	−0.16	−0.47	−0.31	0.56	−0.93	0.55	0.87	0.17	0.18	**0.004**	**0.001**	0.66	0.18
6	0.34	−0.80	−0.73	−0.62	0.34	0.30	0.70	0.97	0.66	0.28	**0.01**	**0.02**	0.18
7	**0.01**	0.37	−0.39	−0.60	−0.67	0.26	0.42	0.65	0.42	0.51	0.17	**0.01**	0.15
8	**0.04**	**0.02**	0.52	−0.37	−0.45	−0.83	0.13	0.77	0.48	0.66	0.70	0.29	0.34

Although the difference-in-means test yields slightly more strongly significant results than the rank sum test, the season/lead patterns of the two approaches are similar. Significant differences are found at short lead time for the target periods near May–July, the seasons just following (and most strongly affected by) the northern spring predictability barrier. This significance pattern migrates to later target periods with increasing lead time, following the target periods corresponding to the fixed forecast start times of April or May. For forecasts whose lead times do not traverse the northern spring barrier, statistical versus dynamical skill differences are not significant.

Although significant differences are noted for specific seasons and leads, there is a multiplicity of candidate season/lead combinations, and 5% of the 108 candidates (i.e., 5 or 6 of them) are expected to be significant by chance. In the case of the Wilcoxon test, 20 entries are significant, and 10 are significant at the 1% level. For the difference-in-means test, 20 entries are significant and 15 are significant at the 1% level. To assess the field significance of the collective results (Livezey and Chen 1983), Monte Carlo simulations are conducted in which the model type is randomly shuffled 5,000 times, maintaining the actual number of dynamical and statistical models for the given lead time, and the set of local significances is regenerated. Using the sum of the Z or t values of all 108 cells as the test statistic, the percentage of the 5,000 randomized cases that exceeds the actual case is determined. The Z or t values are taken as positive when the correlation of the dynamical models exceeds that of the statistical models, and negative for the opposite case. The resulting field significances are 0.034 and 0.026 for the Wilcoxon rank test and t test, respectively, indicating significantly low probabilities that the set of local significances occurred accidentally. This finding suggests that the circumstance under which local significance is found, namely forecasts impacted by the northern spring predictability barrier being more successful in dynamical than statistical models, is meaningful and deserves fuller explanation.

A likely reason that dynamical models are better able to predict ENSO through the time of year when transitions (dissipation of old events and/or development of new events) typically occur is their more effective detection, through the initial conditions, of new evolution in the ocean–atmosphere system on a relatively short (i.e., intramonth) time scale—evolution that may go unnoticed by statistical models that use monthly or seasonal means for their predictor variables. Additionally, dynamical models are capable of nonlinear compounding effects of anomaly growth due to their time-marching design using small time steps, enabling fast evolution. While the details of such rapidly evolving scenarios indicated in a single model run may not have a high probability of actually occurring, consideration of predictions from an ensemble of many runs helps to define such probabilities. Statistical models might be able to compete better against dynamical models if they used finer temporal resolution, such as weekly means. Although use of coarser temporal resolution reduces noise and may serve a purpose similar to using large ensembles in dynamical models, there are circumstances under which rapid recent evolution on shorter time scales is crucial to successful prediction.

Statistical models need long histories of predictor data to develop their predictor–predictand relationships. This need presents a problem in using the three-dimensional observations in the tropical Pacific, such as the data from the Tropical Atmosphere Ocean–Triangle Trans-Ocean Buoy Network (TAO-TRITON) array (McPhaden et al. 1998), which dates from the 1990s. [However, some subsurface tropical Pacific data date back 10 or more years earlier in the eastern portion of the basin, and are available in the NCEP Global Ocean Data Assimilation System (GODAS) product.] This shorter data history precludes robust empirical definition of their predictive structures, and thus they are often omitted in statistical models. Although comprehensive dynamical models require a data history sufficient for verification and as a basis for defining anomalies, such a history is not basic to their functioning, and real-time predictions are able to take advantage of improved observing systems as they become available, potentially resulting in better initial conditions. While use of such crucial data suggests that dynamical models should be able to handily outperform statistical models, dynamical models have been burdened by problems such as initialization errors related to problems in data analysis/assimilation, and biases or drifts stemming from imperfect numerical representation of critical air–sea physics and parameterization of small-scale processes. As these weaknesses have improved, some comprehensive dynamical models have begun demonstrating their higher theoretical potential, and although they are much more costly than statistical models their performance may continue to increase (Chen and Cane 2008).

Real-time predictive skill versus longer-period hindcast skill. Because 9 years is too short a period from which to determine predictive skill levels with precision (Table 3), one reasonably might ask to what extent the performance levels sampled here could be expected to hold for future predictions. To achieve more robust skill estimates, a commonly used strategy is to increase the sample of predictions by generating retrospective hindcasts—"predictions" for past decades using the same model and procedures as in real time, to the extent possible. Cross-validation schemes are often used with statistical models, where varying sets of one or more years are withheld from the full dataset, and the remaining years are used to define the prediction model, which then is used to forecast the withheld year(s) (Michaelsen 1987). However, this sequential withholding technique can result in a negative skill bias under low skill conditions (Barnston and Van den Dool 1993) and/or a positive skill bias when information "leaks" into the training samples because some predictors or parameters have been selected using the same (or a similar) full dataset. In practice, there is no comparable procedure applied in dynamical model development, and model parameter choices are often made using the same data used to evaluate skill.

Fourteen of the 20 models whose 9-yr real-time forecast performance was discussed above (6 dynamical, 8 statistical) have produced hindcasts available to this study for the approximately 30-yr period of 1981 (or 1982) to 2011. To assess the consistency of their skills during the longer period and the 9-yr period of real-time predictions, the temporal correlation between hindcasts and observations is examined as a function of target seasons and lead time. Figure 14 shows a comparison of the correlation skills for the 9-yr real-time predictions (as in Fig. 5) and the 30-yr hindcasts for the subset of models having both datasets. Although the correlation plots are roughly similar, inspection shows generally higher hindcast skill levels for all of the models. Why do the hindcasts have higher skills? One explanation is that the 2002–11 period may have been more difficult to predict than most of the longer period. Another explanation is that skills tend to be higher in hindcasts than in real-time predictions because the cross-validation design may still allow inclusion of some artificial skill.

To assess the relative difficulty of the recent 9-yr period, the time series of uncentered correlation skills[9] of sliding 9-yr periods, each phased 1 yr apart, are examined for the 22 running periods within 1981–2010. The resulting time series of correlation are shown in Fig. 15 (top), for lead times of 3 months and 6 months. It is clear that for all models, and for both lead times, the 2002–10 period, as well as the early to middle 1990s, posed a greater predictive challenge than most of the last three decades. As noted earlier, distinguishing features of the 2002–11 period have been 1) a lower amplitude of variability (no very strong events; Table 2); and 2) greater consecutive year alternations between El Niño and La Niña (Fig. 3). The former feature may be expected to reduce the upper limit of correlation skill by reducing the signal part of the signal-to-noise ratio. If the noise component remains approximately constant, and signal strength is somewhat restricted as during 2002–10, then the correlation is reduced. The bottom inset of Fig. 15 (top) shows the 9-yr running standard deviation of the observed Nino-3.4 SST anomalies, with respect to the 1981–2010 mean. The correlation between the running standard deviation and the model average skill is about 0.8 for both 3- and 6-month lead

[9] For the uncentered correlation, the 9-yr means are not removed, so that standardized anomalies with respect to the 30-yr means, rather than the 9-yr means, are used in the cross products and the standard deviation terms.

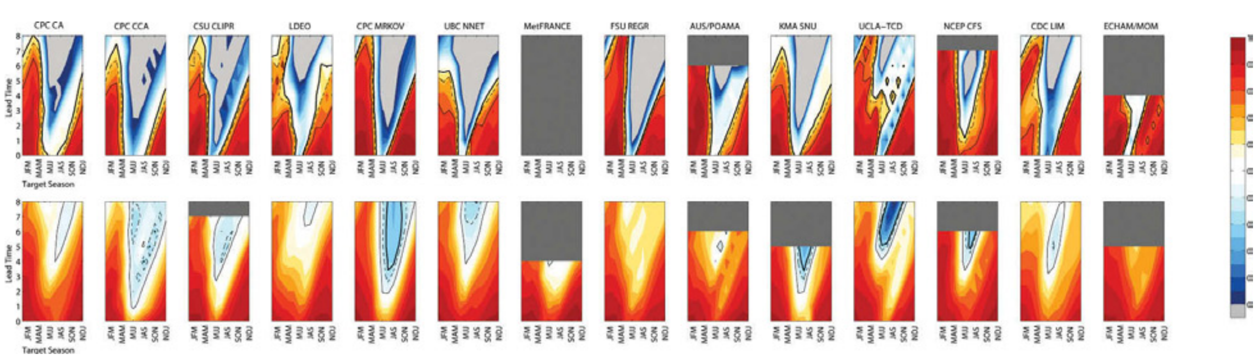


Fig. 14. Temporal correlation between model forecasts and observations as a function of target season and lead time for (top) real-time forecasts (as in Fig. 5) and (bottom) hindcasts for the 1981–2010 period for models having long-term hindcasts. The thick solid contour shows the 90% significance level, the dashed contour the 95% level, and the thin solid contour the 99% level for sample sizes of (top) 9 and (bottom) 30.

predictions, confirming a strong relationship between signal strength and correlation skill.

The average of the anomaly of the 2002–11 correlation with respect to that over 1981–2010 is approximately −0.14 (0.61 vs 0.75) for 3-month lead forecasts and −0.23 (0.42 vs 0.65) for 6-month lead forecasts. The −0.23 "difficulty anomaly" for 6-month lead forecasts is of greater magnitude than the deficit in skill of the real-time predictions during 2002–11 compared with the approximately 0.6 skill level found in earlier studies, suggesting that today's models would slightly (and statistically insignificantly) outperform those of the 1990s if the decadal fluctuations of the nature of ENSO variability were taken into account.

To examine the signal versus skill relationship with more temporal precision, a 3-yr time window is used in Fig. 15 (bottom), the bottom inset again indicating the running standard deviation. Within the 2002–10 period, the subperiod of 2003–07, in between the 2002/03 El Niño and the 2007/08 La Niña, is a focal point of low skill and low variability. The correlation between the 3-yr running standard deviation and model average skill is about 0.78 for both 3- and 6-month lead predictions, confirming a strong linkage between signal strength and correlation skill with higher temporal resolution.

A second cause of the recent real-time predictions having lower correlation skill than the 30-yr hindcasts is that using a period for which the verifying observations exist may permit inclusion of some artificial skill not available in real-time predictions. Attempts to design the predictions in a manner simulating the real-time condition (e.g., cross validation) reduce artificial skill, but subtle aspects involving predictor selection within a finite group of commonly used datasets often prevent its total elimination. A completely retroactive design, in which training only on years earlier than the year being forecast is permitted, may be a purer simulation of the real-time situation. Another impediment to the skill of real-time predictions includes such unavoidable inconveniences as delays in availability of predictor or initialization data,

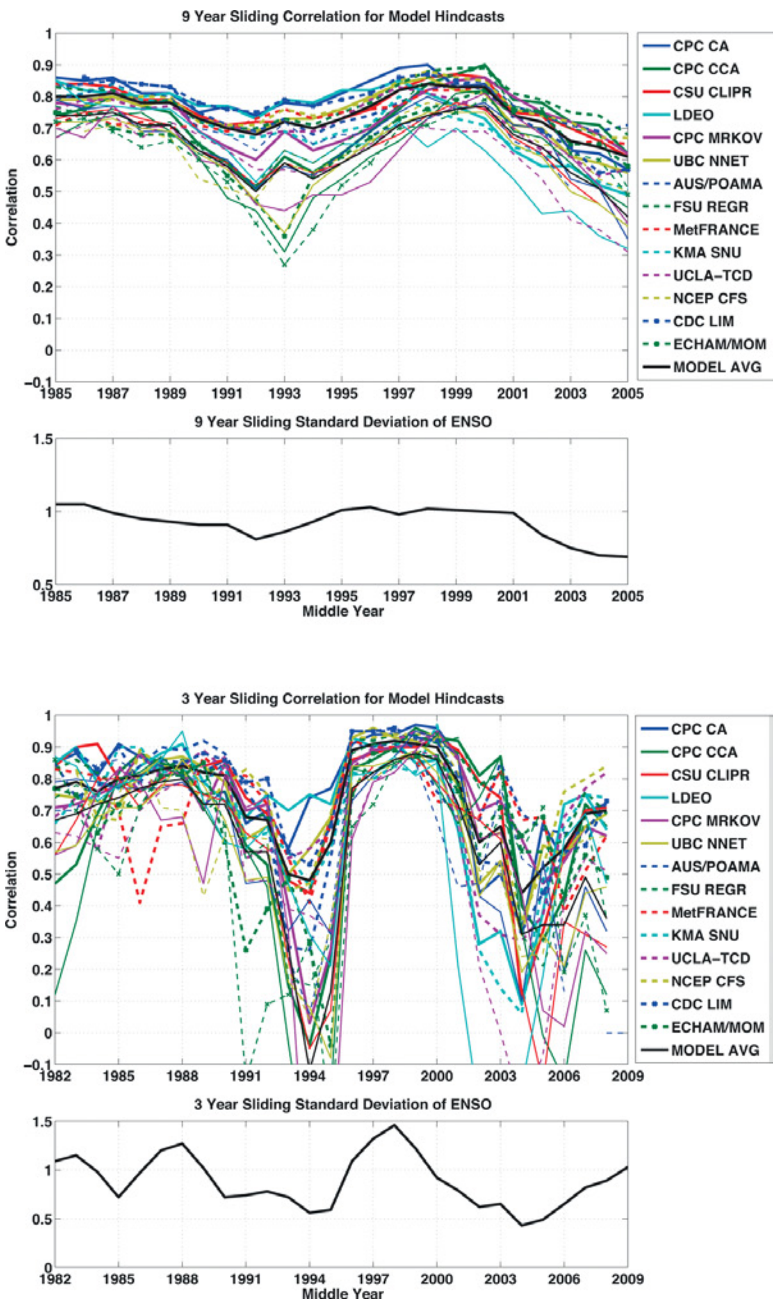


Fig. 15. (top) Time series of uncentered correlations between predictions of given individual models and observations for sliding 9-yr periods, phased 1 yr apart, for the 21 or 22 running 9-yr periods within 1981–2010. Correlations for forecasts at lead times of 3 months (thick lines) and 6 months (thin lines) are shown. Inset below main panel shows the standard deviation of observed SST anomalies for each sliding 9-yr period, with respect to the 1981–2010 mean. (bottom) As at top, except for sliding 3-yr periods for the 27 or 28 running 3-yr periods within 1981–2010.

computer failure or other unforeseen emergencies, or human error. While this factor may seem minor, experience with the ENSO prediction plume has shown that such events occur more than once in a while.

Target period slippage was found in the real-time predictions, and one reasonably might expect it to appear in the longer-term hindcasts also. Figure 16 compares slippage in the selected models' hindcasts and corresponding real-time predictions and reveals a milder degree of slippage in the hindcasts. Could this difference be related to the higher average skill over the 30-yr period than its most recent 9 years? Verifications on sliding 9-yr periods show that slippage is greater during periods of lower average correlation skill (not shown). This finding suggests that slippage is most prominent when total error is greatest, which is the case for longer lead times and for seasons most impacted by the northern spring predictability barrier. When skill is relatively low, the models tend to err in the direction of missing the onset of new events (or being late in predicting the end of events), as opposed to predicting new events that turn out to be false alarms or ending events too early. In other words, the models are too persistent. During very strong events this bias is offset by high skill during the period when the event remains at high amplitude, since quasi-persistence is then an excellent forecast out to a longer lead time than is typically the case.

DISCUSSION AND CONCLUSIONS.

Verification of the real-time ENSO prediction skills of 20 models (12 dynamical, 8 statistical) during 2002–11 indicates skills somewhat lower than those found for the less advanced models of the 1980s and 1990s. However, this apparent retrogression in skill is explained by the fact that the 2002–11 study period was demonstrably more challenging for ENSO prediction than most of the 1981–2010 period, due to a somewhat lower variability. A similar situation is found during the 9-yr period centered on the early 1990s. Thirty-year hindcasts for the 1981–2010 period yielded average correlation skills of 0.65 at 6-month lead time, but the real-time predictions for 2002–11 produced only 0.42. The fact that the recent predictions were made in real time, in contrast to the partially hindcast design in the earlier studies, introduces another difference with consequences difficult to quantify but more likely to decrease than increase the recent performance measures.

Based solely on the variability of 9-yr correlation skills of the hindcasts within the 30-yr period, ENSO prediction skill is slightly higher using today's models than those of the 1990s (0.65 vs about 0.6 correlation). *Decadal variability of ENSO predictability can strongly dominate the gradual skill improvements related to real advances in ENSO prediction science and models.*

Both real-time predictions and hindcasts have a tendency to verify with higher skill against observations occurring earlier than the intended forecast target period—a tendency that increases with increasing lead time. This "slippage" is related to systematically sluggish transitions: initiating new ENSO events too late and too weakly, and failing to end events on time. Slippage is more pronounced during multiyear periods of relatively weaker variability and skill, and for predictions starting from the time of year when ENSO transitions are most likely (March through May).

Unlike earlier results, the sample mean of skill of the dynamical models exceeds that of statistical models for start times between March and May when prediction has proven most challenging. Utilizing the fairly large numbers of dynamical and statistical models, the skill difference between the two model types is statistically significant under these seasonal

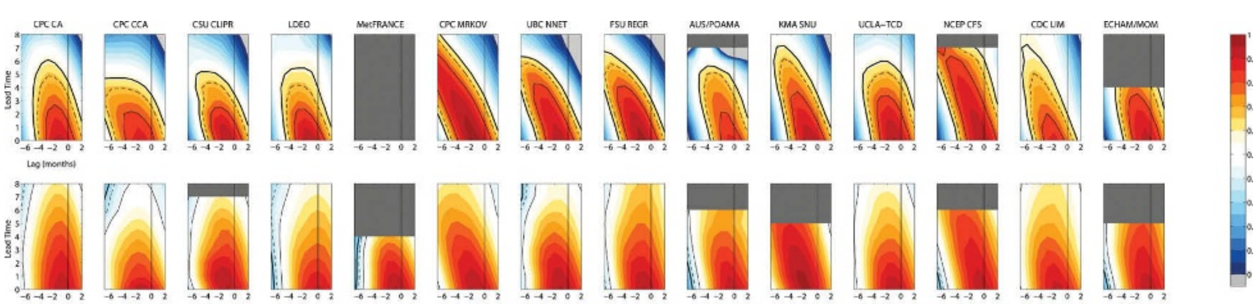


FIG. 16. Temporal correlation between model predictions and observations as a function of lag time and lead time for (top) real-time forecasts (as in Fig. 12) and (bottom) hindcasts for the 1981–2010 period for models having long-term hindcasts. The thick solid contour shows the 90% significance level, the dashed contour the 95% level, and the thin solid contour the 99% level for sample sizes of (top) 9 and (bottom) 30.

conditions based on just 9 years of data, accepting this 2002–11 period as an unbiased and fixed condition of the analysis. The skill comparison by model type also passes a field significance test for all seasons and leads collectively, at the $p = 0.03$ level. The slightly greater dynamical skill is largely attributable to the most advanced and costly fully coupled ocean–atmosphere prediction systems having highest spatial resolution, using today's most advanced data assimilation systems for initialization (e.g., Balmaseda and Anderson 2009), and having the largest set of ensemble predictions. This finding suggests that continued implementation of better assimilation schemes for more realistic initial conditions, more detailed physics, higher resolution, and larger ensemble sizes makes additional advances in skill likely.

Why are the most comprehensive dynamical models found better able to predict ENSO than simpler dynamical models or statistical models through the time of year when ENSO transitions typically occur (previous episodes decay, or new episodes emerge)? A likely reason is their more effective detection and usage, through their initial conditions, of new information in the ocean–atmosphere system on a short (i.e., intramonth) time scale—information that may not play a major role in statistical models that use longer time means for their predictor variables. Statistical models may have potential for higher skill if their predictors were designed with finer temporal resolution. Because funding policy over the last two decades has favored dynamical over statistical prediction research proposals, the relatively greater advances in dynamical model skill is not surprising. Thus, while the major global forecast producing centers have come out with improved versions of their dynamical models every several years, most of the statistical models in this study have remained fundamentally unchanged over the last decade, and several even since the 1980s or 1990s [e.g., CPC Markov, CDC LIM, CPC CA, CPC CCA, the Colorado State University climatology–persistence model (CSU CLIPR), and UBC NNET].

However, aside from the funding preference factor, dynamical models are capable of nonlinear compounding effects of anomaly growth due to their time-marching design using small time steps, enabling faster ENSO state evolution than statistical models. Statistical models need long histories of predictor data to develop their predictor–predictand relationships, but the three-dimensional observations across much of the tropical Pacific (e.g. from the TAO-TRITON array) began only in the 1990s, precluding a robust empirical definition of their predictive relationships. Thus, these subsurface tropical Pacific predictors may be omitted in some statistical models. Comprehensive dynamical models require a data history for verification and for defining anomalies, but real-time predictions are possible without such a history, as data from current observing systems are available for their initial conditions.

On the other hand, dynamical models still have major specific problems such as initialization errors due to the details of data analysis/assimilation, and biases or drifts stemming from imperfect numerical representation of critical air–sea physics and parameterization of small-scale processes. As these weaknesses have improved, some of the comprehensive dynamical models have begun demonstrating their higher potential and may eventually prove to be the standard in ENSO prediction as they did decades ago in numerical weather forecasting. However, because of the profound fundamental differences between weather prediction and seasonal climate prediction, one cannot assume parallel evolutions of methodologies. In particular, seasonal climate is a large aggregation of running weather activity that collectively behaves in a considerably more linear fashion than its constituent weather activity, making it generally more amenable to statistical modeling than daily weather. For this reason, dynamical model skill has been slow to exceed statistical model skill in seasonal climate and/or ENSO prediction, and there is still an important role for statistical/empirical climate prediction when dynamical approaches fail to deliver useful predictions.

In conclusion, during the recent decade dynamical ENSO prediction models outperformed their statistical counterparts to a slight but statistically significant extent, primarily because of their better forecasts when traversing the northern spring predictability barrier. While doubt may be cast regarding whether the much greater cost of dynamical prediction is worth the benefit in performance, this cost is expected to decrease with time as science and engineering continue to advance.

ACKNOWLEDGMENTS. The authors appreciate the thoughtful comments and suggestions of the anonymous reviewers. Klaus Wolter provided a set of penetrating and useful comments and requests, leading to considerable improvements in the final paper. This work was funded by a grant/cooperative agreement from the National Oceanic and Atmospheric Administration (NA050AR4311004). The views expressed are those of the authors and do not necessarily reflect the views of NOAA or its subagencies.

REFERENCES

Alves, O., M. A. Balmaseda, D. Anderson, and T. Stockdale, 2004: Sensitivity of dynamical seasonal forecasts to ocean initial conditions. *Quart. J. Roy. Meteor. Soc.,* **130,** 647–667.

Anderson, D., and Coauthors, 2003: Comparison of the ECMWF seasonal forecast systems 1 and 2, including the relative performance for the 1997/98 El Niño. ECMWF Tech. Memo. 404, 93 pp.

——, and Coauthors, 2007: Development of the ECMWF seasonal forecast system 3. ECMWF Tech. Memo. 503, 56 pp.

Arribas, A., and Coauthors, 2011: The GloSea4 ensemble prediction system for seasonal forecasting. *Mon. Wea. Rev.,* **139,** 1891–1910.

Bacmeister, J. T., P. J. Pegion, S. D. Schubert, and M. J. Suarez, 2000: Atlas of seasonal means simulated by the NSIPP1 atmospheric GCM. NASA TM-2000-104606, Vol. 17, 194 pp. [Available online at http://gmao.gsfc.nasa.gov/pubs/docs/Bacmeister133.pdf.]

Balmaseda, M. A., 2004: Ocean data assimilation for seasonal forecasts. *Proc. ECMWF Seminar on Recent Developments in Data Assimilation for Atmosphere and Ocean,* Reading, United Kingdom, ECMWF, 301–325.

——, and D. Anderson, 2009: Impact of initialization strategies and observations on seasonal forecast skill. *Geophys. Res. Lett.,* **36,** L01701, doi:10.1029/2008GL035561.

——, A. Vidard, and D. Anderson, 2008: The ECMWF ocean analysis system: ORA-S3. *Mon. Wea. Rev.,* **136,** 3018–3034.

Barnett, T. P., and R. W. Preisendorfer, 1987: Origins and levels of monthly and seasonal forecast skill for United States surface air temperatures determined by canonical correlation analysis. *Mon. Wea. Rev.,* **115,** 1825–1850.

——, M. Latif, N. Graham, M. Flügel, S. Pazan, and W. White, 1993: ENSO and ENSO-related predictability. Part I: Predictions of equatorial Pacific sea surface temperature with a hybrid coupled ocean–atmosphere model. *J. Climate,* **6,** 1545–1566.

Barnston, A. G., and C. F. Ropelewski, 1992: Prediction of ENSO episodes using canonical correlation analysis. *J. Climate,* **5,** 1316–1345.

——, and H. M. van den Dool, 1993: A degeneracy in cross-validated skill in regression-based forecasts. *J. Climate,* **6,** 963–977.

——, and Coauthors, 1994: Long-lead seasonal forecasts—Where do we stand? *Bull. Amer. Meteor. Soc.,* **75,** 2097–2114.

——, M. Chelliah, and S. B. Goldenberg, 1997: Documentation of a highly ENSO-related SST region in the equatorial Pacific. *Atmos.–Ocean.* **35,** 367–383.

——, M. H. Glantz, and Y. He, 1999: Predictive skill of statistical and dynamical climate models in SST forecasts during the 1997/98 El Niño episode and the 1998 La Niña onset. *Bull. Amer. Meteor. Soc.,* **80,** 217–243.

Cane, M. A., S. E. Zebiak, and S. C. Dolan, 1986: Experimental forecasts of El Niño. *Nature,* **321,** 827–832.

Chen, D., and M. A. Cane, 2008: El Niño prediction and predictability. *J. Comput. Phys.,* **227,** 3625–3640.

——, S. E. Zebiak, A. J. Busalacchi, and M. A. Cane, 1995: An improved procedure for El Niño forecasting: Implications for predictability. *Science,* **269,** 1699–1702.

——, M. A. Cane, A. Kaplan, S. E. Zebiak, and D. Huang, 2004: Predictability of El Niño in the past 148 years. *Nature,* **428,** 733–736.

Clarke, A. J., and S. Van Gorder, 2001: ENSO prediction using an ENSO trigger and a proxy for western equatorial Pacific warm pool movement. *Geophys. Res. Lett.,* **28,** 579–582.

——, and ——, 2003: Improving El Niño prediction using a space–time integration of Indo-Pacific winds and equatorial Pacific upper ocean heat content. *Geophys. Res. Lett.,* **30,** 1399, doi:10.1029/2002GL016673.

Danabasoglu, G., W. G. Large, J. J. Tribbia, P. R. Gent, B. P. Briegleb, and J. C. McWilliams, 2006: Diurnal coupling in the tropical oceans of CCSM3. *J. Climate,* **19,** 2347–2365.

Davis, R. E., 1979: A search for short range climate predictability. *Dyn. Atmos. Oceans,* **3,** 485–497.

Déqué, M., C. Dreveton, A. Braun, and D. Cariolle, 1994: The ARPEGE/IFS atmosphere model: A contribution to the French community climate modeling. *Climate Dyn.,* **10,** 249–266.

DeWitt, D. G., 2005: Retrospective forecasts of interannual sea surface temperature anomalies from 1982 to present using a directly coupled atmosphere–ocean general circulation model. *Mon. Wea. Rev.,* **133,** 2972–2995.

Gibelin, A. L., and M. Déqué, 2003: Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. *Climate Dyn.,* **20,** 327–339.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood, 2000: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dyn.,* **16,** 147–168.

Guilyardi, E., A. Wittenberg, A. Fedorov, M. Collins, C. Wang, A. Capotondi, G. J. van Oldenborgh, and

T. Stockdale, 2009: Understanding El Niño in ocean–atmosphere general circulation models: Progress and challenges. *Bull. Amer. Meteor. Soc.*, **90,** 325–340.
Hayes, W. L., 1973: *Statistics for the Social Sciences*. Holt, Rinehart and Winston, 954 pp.
Hsieh, W. W., and B. Tang, 1998: Applying neural network models to prediction and data analysis in meteorology and oceanography. *Bull Amer. Meteor. Soc.,* **79,** 1855–1870.
Hudson, D., O. Alves, H. H. Hendon, and G. Wang, 2011: The impact of atmospheric initialization on seasonal prediction of tropical Pacific SST. *Climate Dyn.,* **36,** 1155–1171.
Ishikawa, I., J. Tsujino, M. Hirabara, H. Nakano, T. Yasuda, and H. Ishizaki, 2005: Meteorological Institute Community Ocean Model (MRI.COM) manual. MRI Tech. Rep. 47, 190 pp.
Ji, M., D. W. Behringer, and A. Leetmaa, 1998: An improved coupled model for ENSO prediction and implications for ocean initialization. Part II: The coupled model. *Mon. Wea. Rev.,* **126,** 1022–1034.
Jin, E. K., and Coauthors, 2008: Current status of ENSO prediction skill in coupled ocean–atmosphere models. *Climate Dyn.*, **31,** 647–664.
JMA, 2007: Outline of the Operational Numerical Weather Prediction at the Japan Meteorological Agency. JMA, 194 pp. [Available online at www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline-nwp/index.htm.]
Keenlyside, N., and R. Kleeman, 2002: Annual cycle of equatorial zonal currents in the Pacific. *J. Geophys. Res.,* **107,** 3093, doi:10.1029/2000JC000711.
Kirtman, B. P., 2003: The COLA anomaly coupled model: Ensemble ENSO prediction. *Mon. Wea. Rev.,* **131,** 2324–2341.
——, and P. S. Schopf, 1998: Decadal variability in ENSO predictability and prediction. *J. Climate,* **11,** 2804–2822.
——, and D. Min, 2009: Multimodel ensemble ENSO prediction with CCSM and CFS. *Mon. Wea. Rev.,* **137,** 2908–2930.
Knaff, J. A., and C. W. Landsea, 1997: An El Niño–Southern Oscillation climatology and persistence (CLIPER) forecasting scheme. *Wea. Forecasting,* **12,** 633–652.
Kondrashov, D., S. Kravtsov, A. W. Robertson, and M. Ghil, 2005: A hierarchy of data-based ENSO models. *J. Climate,* **18,** 4425–4444.
Kousky, V. E., and R. W. Higgins, 2007: An alert classification system for monitoring and assessing the ENSO cycle. *Wea. Forecasting,* **22,** 353–371.
Kravtsov, S., D. Kondrashov, and M. Ghil, 2005: Multilevel regression modeling of nonlinear processes: Derivation and applications to climatic variability. *J. Climate,* **18,** 4404–4424.
Kug, J.-S., I.-S. Kang, and S. E. Zebiak, 2001: The impacts of the model assimilated wind stress data in the initialization of an intermediate ocean and the ENSO predictability. *Geophys. Res. Lett.,* **28,** 3713–3716.
Landsea, C. W., and J. A. Knaff, 2000: How much skill was there in forecasting the very strong 1997/98 El Niño? *Bull. Amer. Meteor. Soc.,* **81,** 2107–2119.
Latif, M., 1987: Tropical ocean circulation experiments. *J. Phys. Oceanogr.,* **17,** 246–263.
——, T. Stockdale, J. Wolff, G. Burgers, E. Maier-Reimer, M. Junge, K. Arpe, and L. Bengtsson, 1994: Climatology and variability in the ECHO coupled GCM. *Tellus,* **46A,** 351–366.
Livezey, R. E., and W. Y. Chen, 1983: Field significance and its determination by Monte Carlo techniques. *Mon. Wea. Rev.,* **111,** 46–59.
Luo, J.-J., S. Masson, S. Behera, S. Shingu, and T. Yamagata, 2005: Seasonal climate predictability in a coupled OAGCM using a different approach for ensemble forecasts. *J. Climate,* **18,** 4474–4497.
McPhaden, M. J., and Coauthors, 1998: The Tropical Ocean–Global Atmosphere observing system: A decade of progress. *J. Geophys. Res.,* **103** (C7), 142 169–142 240.
Michaelsen, J., 1987: Cross-validation in statistical climate forecast models. *J. Climate Appl. Meteor.,* **26,** 1589–1600.
Murphy, A. H., 1988: Skill scores based on the mean square error and their relationships to the correlation coefficient. *Mon. Wea. Rev.,* **116,** 2417–2424.
Pacanowski, R. C., and S. M. Griffies, 1998: MOM 3.0 Manual. NOAA/Geophysical Fluid Dynamics Laboratory, 608 pp.
Penland, C., 1989: Random forcing and forecasting using principal oscillation pattern analysis. *Mon. Wea. Rev.,* **117,** 2165–2185.
——, and T. Magorian, 1993: Prediction of Niño-3 sea surface temperatures using linear inverse modeling. *J. Climate,* **6,** 1067–1076.
——, and P. D. Sardeshmukh, 1995: The optimal growth of tropical sea surface temperature anomalies. *J. Climate,* **8,** 1999–2024.
Pierce, D. W., 1996: The hybrid coupled model, version 3: Technical notes. Scripps Institution of Oceanography Reference Series 96-27, 66 pp.
Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. *J. Climate,* **15,** 1609–1625.
Roeckner, E., and Coauthors, 1996: The atmospheric general circulation model ECHAM4: Model description

and simulation of present day climate. MPI Rep. 218, Max-Planck-Institut für Meteorologie, 90 pp.

Rowell, D. P., 1998: Assessing potential seasonal predictability with an ensemble of multidecadal GCM simulations. *J. Climate,* **11,** 109–120.

Saha, S., and Coauthors, 2006: The NCEP Climate Forecast System. *J. Climate,* **19,** 3483–3517.

Schopf, P., and A. Loughe, 1995: A reduced-gravity isopycnic ocean model: Hindcasts of El Niño. *Mon. Wea. Rev.,* **123,** 2839–2863.

Stockdale, T. N., and Coauthors, 2011: ECMWF seasonal forecast system 3 and its prediction of sea surface temperature. *Climate Dyn.,* **37,** 455–471, doi:10.1007/s00382-010-0947-3.

Tangang, F. T., W. W. Hsieh, and B. Tang, 1997: Forecasting the equatorial Pacific sea surface temperatures by neural network models. *Climate Dyn.,* **13,** 135–147.

——, B. Tang, A. H. Monahan, and W. W. Hsieh, 1998: Forecasting ENSO events: A neural network–extended EOF approach. *J. Climate,* **11,** 29–41.

Tippett, M. K., A. G. Barnston, and S. Li, 2012: Performance of recent multimodel ENSO forecasts. *J. Appl. Meteor. Climatol.,* **9,** 637–654.

Van den Dool, H. M., 1994: Searching for analogues, how long must we wait? *Tellus,* **46A,** 314–324.

——, 2007: *Empirical Methods in Short-Term Climate Prediction*. Oxford University Press, 215 pp.

Wang, G., R. Kleeman, N. Smith, and F. Tseitkin, 2002: The BMRC coupled general circulation model ENSO forecast system. *Mon. Wea. Rev.,* **130,** 975–991.

——, ——, D. Hudson, H. Hendon, G. Liu, and F. Tseitkin, 2008: SST skill assessment from the new POAMA-1.5 system. *BMRC Research Letter,* No. 8, Bureau of Meteorology Research Centre, Melbourne, Australia. [Available online at http://cawcr.gov.au/bmrc/pubs/researchletter/reslett_08.pdf.]

Wang, W., M. Chen, and A. Kumar, 2010: An assessment of the CFS real-time seasonal forecasts. *Wea. Forecasting,* **25,** 950–969.

Wolff, J., E. Maier-Reimer, and S. Legutke, 1997: The Hamburg Ocean Primitive Equation Model. Deutsches Klimarechenzentrum Tech. Rep. 13, 98 pp.

Xue, Y., M. A. Cane, S. E. Zebiak, and M. B. Blumenthal, 1994: On the prediction of ENSO: A study with a low-order Markov model. *Tellus,* **46A,** 512–528.

——, A. Leetmaa, and M. Ji, 2000: ENSO prediction with Markov models: The impact of sea level. *J. Climate,* **13,** 849–871.

Zaliapin, I., and M. Ghil, 2010: A delay differential model of ENSO variability—Part 2: Phase locking, multiple solutions and dynamics of extrema. *Nonlinear Processes Geophys.,* **17,** 123–135.

Zebiak, S. E., and M. A. Cane, 1987: A model El Niño–Southern Oscillation. *Mon. Wea. Rev.,* **115,** 2262–2278.

Zhang, R.-H., S. E. Zebiak, R. Kleeman, and N. Keenlyside, 2003: A new intermediate coupled model for El Niño simulation and prediction. *Geophys. Res. Lett.,* **30,** 2012, doi:10.1029/2003GL018010.

Zhao, M., and H. H. Hendon, 2009: Representation and prediction of the Indian Ocean dipole in the POAMA seasonal forecast model. *Quart. J. Roy. Meteor. Soc.,* **135,** 337–352.

SINGLE AIRCRAFT INTEGRATION OF REMOTE SENSING AND IN SITU SAMPLING FOR THE STUDY OF CLOUD MICROPHYSICS AND DYNAMICS

BY ZHIEN WANG, JEFFREY FRENCH, GABOR VALI, PERRY WECHSLER, SAMUEL HAIMOV, ALFRED RODI, MIN DENG, DAVE LEON, JEFF SNIDER, LIRAN PENG, AND ANDREW L. PAZMANY

Radar, radiometer, lidar, and in situ sensors working together aboard the University of Wyoming's King Air yield more complete descriptions of clouds than possible when combining ground-based remote sensing with airborne in situ measurements.

Poor understanding of cloud–radiation–dynamics feedbacks results in large uncertainties in forecasting human-induced climate changes (Soden and Held 2006; Solomon et al. 2007). Improving our understanding of cloud physics based on observational data is a critical step to improve physically based cloud microphysics parameterizations for climate and weather models (NRC 1998; Randall et al. 2003; Stoelinga et al. 2003; Fritsch and Carbone 2004; Klein et al. 2009). Airborne in situ cloud observations have played an important role in advancing our understanding of cloud microphysical and dynamic processes by providing detailed measurements at high temporal and spatial resolution (Rangno and Hobbs 1991 and 2001; Heymsfield and Miloshevich 1993; Stevens et al. 2003; Baker and Lawson 2006; McFarquhar et al. 2007; Bailey and Hallett 2009). However, these detailed measurements are only available along a line defined by the flight path of the aircraft. Interpretation of hydrometeor measurements from in situ probes is further limited because of their small sample volumes ranging from ~1 to ~10^5 cm^3 s^{-1}. The small sampling volume, particularly for ice crystals and drizzle drops, is an issue when one wishes to study atmospheric properties with strong spatial inhomogeneity or low concentration (Isaac and Schmidt 2009).

Airborne remote sensing overcomes these weaknesses of in situ sampling; however, the measurements

AFFILIATIONS: WANG, FRENCH, VALI, WECHSLER, HAIMOV, RODI, DENG, LEON, SNIDER, AND PENG—Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming; PAZMANY—ProSensing, Inc., Amherst, Massachusetts
CORRESPONDING AUTHOR: Zhien Wang, Department of Atmospheric Science, University of Wyoming, Dept. 3038, 1000E University Ave. Laramie, WY 82071
E-mail: zwang@uwyo.edu

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-11-00044.1

In final form 20 December 2011

reflect integrated cloud properties, not the size-resolved distributions of in situ sampling. In addition to measures of hydrometeor properties, airborne radars provide unique measurements of cloud-, precipitation-, and cloud-scale dynamics (Hildebrand et al. 1996; Heymsfield et al. 1996; Vali et al. 1998; Stevens et al. 2003; Damiani et al. 2006; Leon et al. 2006). Lidars operate at much shorter wavelengths than radars and have capabilities to measure aerosols and optically thin clouds (McGill et al. 2002; Wang et al. 2009). Because these two types of active remote sensors, plus radiometers, have different sensitivities to particles of different size, it is possible to optimally combine multiple remote sensor measurements in cloud macrophysical and microphysical property retrievals (Wang and Sassen 2001, 2002; Stephens et al. 2002).

Integration of the complementary capabilities of airborne in situ sampling and remote sensing has great advantages for the study of atmospheric processes. For example, 2D cross sections of cloud microphysical properties retrieved from remote sensor measurements provide a context to understand detailed in situ cloud measurements. The integration of in situ and remote sensing can be achieved with one or more aircrafts in a field campaign. The National Aeronautics and Space Administration (NASA) Cirrus Regional Study of Tropical Anvils and Cirrus Layers–Florida-Area Cirrus Experiment (CRYSTAL-FACE; www.espo.nasa.gov/crystalface/index.html) in 2002 is a great example of multiple-aircraft remote sensing and in situ sampling integration. However, even with carefully coordinated multiple aircraft flights, CRYSTAL-FACE data demonstrated the difficulty in acquiring spatially and temporally collocated data (Wang et al. 2005) with multiple aircraft.

Airborne research at the University of Wyoming began nearly 50 years ago. Since the mid-1960s, researchers at the university have utilized three different aircraft to acquire measurements throughout the lower troposphere (Rodi 2011). The University of Wyoming King Air (UWKA), the most current aircraft, is a specially modified Beechcraft Super King Air 200T for research in the lower to midtroposphere, including cloud physics studies. It was originally

Table 1. A list of major cloud physics and aerosol instrumentation on the UWKA.

Instrument	Capability
Remote sensing	
WCR	Z_e and Doppler velocity
WCL	Backscattering coefficient and linear depolarization ratio
GVR	LWP and total PWV
In situ sampling (hydrometeor)	
DMT CDP	Cloud droplet size spectra within 2–50 μm (30 channels)
PMS FSSP	Cloud droplet size spectra [15 channels with lower and upper limits typically set at 1.5 and 47.5 μm; Vali et al. (1998)]
PMS OAP-2DC	Two-dimensional particle images [20 channels with lower and upper limits set at 25 and 7,000 μm, respectively; Gordon and Marwitz (1984)]
Fast OAP-2DC grayscale with 64 diodes	Two-dimensional particle images (100 channels with bin boundaries starting at 13 μm and extending to 2,513 μm in 25-μm increments)
PMS OAP-2DP	Two-dimensional particle images [20 channels with lower and upper limits set at 100 and 10,000 μm, respectively; Gordon and Marwitz (1984)]
Gerber PVM 100A	Cloud liquid water content from droplets up to ~60 μm
DMT LWC100 (hotwire)	Cloud liquid water content from droplets up to ~50 μm
Rosemount ice detector	Super-cooled liquid water content/icing rate
In situ sampling (aerosol)	
TSI CPC3010 (CN counter)	Aerosol particle concentrations larger than 15 nm
TSI CPC3025	Aerosol particle concentrations larger than 3 nm
DMT PCASP with SPP200	Aerosol size spectra [30 channels with upper and lower limits set at 0.1 and 3 μm; Snider and Petters (2008)]

funded through the U.S. Bureau of Reclamation, and since its acquisition in 1977 the UWKA participated in experiments throughout the United States and in many parts of the world, funded by numerous federal and international agencies. Since 1988 the UWKA has been operated as a national facility through a cooperative agreement between the University of Wyoming and the National Science Foundation (NSF; www.eol.ucar.edu/instrumentation).

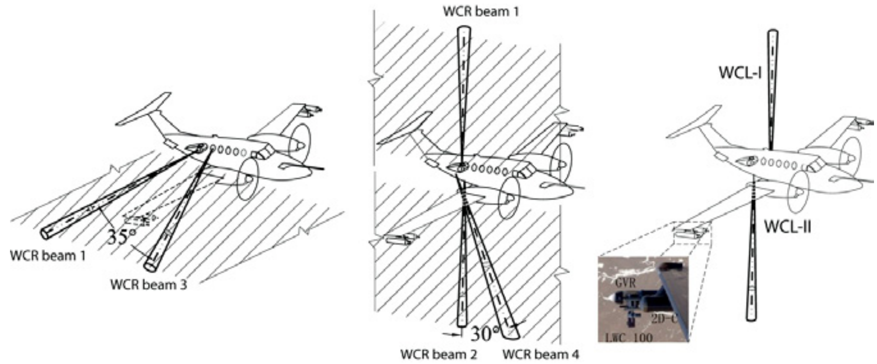


Fig. 1. A schematic of the UWKA configuration illustrating the location and looking directions for the remote sensing instruments WCR, WCL, and GVR. The inset shows one set of the wingtip-mounted pods holding the in situ cloud physics probes.

Over the last two decades there has been a concerted effort by investigators from the University of Wyoming, funded through NSF, NASA, and the Office of Naval Research, to develop a single aircraft integration of cloud radar and in situ sampling capabilities for cloud studies (Vali et al. 1995; French et al. 1999; Galloway et al. 1999). The recent addition of the Wyoming Cloud Lidar (WCL; Wang et al. 2009) led to a more complete integrated cloud observation capability on the UWKA, as part of U.S. NSF-funded Lower Atmospheric Observing Facilities (LAOF). The Wyoming Cloud Radar (WCR) and the WCL are also available for deployment on the NSF–National Center for Atmospheric Research (NCAR) C130 research aircraft. Further, the development of a 183-GHz microwave radiometer (Pazmany 2007) and its initial airborne testing on the UWKA and the NSF-C130 aircraft demonstrated the potential for an even more expanded capability. Clearly, the integration of in situ and remote sensors on a single aircraft offers important advantages from an economic and logistical point of view and allows sampling in fixed spatial relation to nonstationary meteorological features. More importantly, as illustrated by examples herein, it offers a new capability for cloud and precipitation studies.

In this paper we present analyses from the integrated remote sensing and in situ capability developed for the UWKA. In this context we present five examples from the Wyoming Airborne Integrated Cloud Observation (WAICO) experiment, a field campaign designed to explore these new capabilities. A sixth example from the Variability of the American Monsoon System (VAMOS) Ocean–Cloud–Atmosphere–Land Study (VOCALS) highlights how this capability can be used on the NSF–NCAR C130 to study different cloud systems.

INSTRUMENTATION. The UWKA team has continually developed new observational capabilities (Rodi 2011) and has most recently evolved as an airborne platform with integrated remote sensing and in situ sampling capabilities for cloud and boundary layer study. Table 1 provides a list of major cloud instrumentation available in UWKA, and Fig. 1 presents a schematic illustration of the instrument configuration.

Wyoming Cloud Radar (95 GHz). The WCR (http://atmos.uwyo.edu/wcr) is a 95-GHz polarimetric Doppler radar utilizing a high-power klystron amplifier to provide up to 2 kW of transmit peak power. A user-controlled and programmable W-band transmit–receive electronic switching network is used to transmit and receive through up to four antennas, as illustrated in Fig. 1. The side antenna beam can be redirected to an upward-pointing beam via an external motorized reflector.

The first deployment of the WCR was in the Small Cumulus Microphysics Study (SCMS) in 1995 (French et al. 1999, 2000) and the Coastal Stratus/Marine Stratocumulus Study (CS) later that same year (Vali et al. 1998). Since that time, the WCR participated in an additional 35 studies, initially as a principal investigator (PI)-supported instrument and as part of the UWKA NSF LAOF since 2004. The WCR continually evolved since its inception as a single-antenna analog radar to today's multiantenna low-noise radar with digital receiver. The original radar was replaced with the current version of WCR in the summer of 2009. The new radar provides 10 dB better detection sensitivity and greater capability for recording more versatile pulse-pair and polarimetric parameters and full Doppler spectra. Table 2 presents the main

Table 2. WCR specifications.

Transmit frequency | Wavelength	94.92 GHz | 3.16 mm
Pulse width | Pulse repetition frequency (PRF)	100–500 ns | 1–20 kHz
Antennas	Aperture | beamwidth
• Side or up (beam 1)	0.305 m | 0.7°
• Side fore (~35°, beam 3)	0.305 m | 0.7°
• Down (near nadir, beam 2)	0.457 m | 0.5°
• Down fore (~30°, beam 4)	0.381 m | 0.6°
Receiver channels	2
• Outputs	Digital (12 bits)
• Dynamic range	65 dB
• Noise figure	5 dB
Sampling rates	
• Along beam	Minimum 7.5 m
• Along flight	Minimum ~3m
Doppler radial velocity processor	
• Pulse pair	1st & 2nd moments
• Fast fourier transform (FFT) spectrum	16–512 spectral lines
Maximum unambiguous Doppler velocity	±15.8 m s^{-1} at 20 kHz PRF
Maximum measurement range	~ 10 km
First usable range gate	~ 100 m

specifications of WCR. A trihedral corner reflector is used to calibrate the up/side antenna on the ground. All other antennas are calibrated relative to that antenna from appropriate weather targets. The absolute accuracy of any of the reflectivity products is estimated to be better than 3 dB. The sensitivity of the radar varies depending on the antenna and the selected acquisition mode with values between –25 and −40 dB*Z* at 1 km. Real-time WCR displays are available for the operator and others onboard the aircraft.

The multibeam configurations of the WCR provide near-simultaneous measurements in horizontal and vertical planes extending from the aircraft flight path. The cross sections of radar reflectivity factor (Z_e) and Doppler velocity are used to characterize cloud and precipitation structure (Pratt et al. 2009; Wood et al. 2011a). Doppler measurements from the two sideward-pointing and the two downward-pointing antennas are used to perform dual-Doppler synthesis in a horizontal plane at the flight level and in a vertical plane along the flight track below the aircraft, rendering a high-resolution (on the order of 50×50 m^2) two-dimensional depiction of cloud and precipitation dynamics (Leon et al. 2006; Damiani and Haimov 2006). Because the WCR backscatter signal from clouds is proportional up to the sixth power of particle size, it is dominated by the largest particles. In nonprecipitating water clouds, the WCR has enough sensitivity to detect returns from cloud droplets alone. However, in mixed-phase clouds, the WCR provides little or no information on the liquid portion of the cloud because the signal is dominated by often larger but much less numerous ice crystals.

Wyoming Cloud Lidar. The WCL is a compact polarization lidar that is used to obtain vertical profiles of backscatter and depolarization ratio. The WCL is designed to complement the WCR by providing additional cloud macrophysical and microphysical properties. For use on the UWKA, the WCL needed to be very compact, with low weight and power consumption, and utilize existing fuselage ports. The upward-pointing WCL (WCL-I) was developed in 2006 and uses a small port just forward of the door. To accommodate the small size of the receiver, a flashlamp-pumped yttrium aluminium garnet (YAG) laser operating at 355 nm is used, providing sufficient power to obtain an acceptable signal-to-noise ratio. The downward WCL (WCL-II; developed in 2007 and 2008) uses a small port near the rear of the fuselage. For this lidar, a 351-nm-wavelength diode-pumped laser was chosen to remain within the envelope of available power on the UWKA. These short wavelengths achieve eye-safe operations and provide stronger signal-to-noise ratios for molecular signals compared to lidars operating at visible or near-infrared wavelengths.

The laser head is integrated with the transmitting and receiving optics into a compact package. This compact design makes it suitable for aircraft installation and provides high mechanical stability to maintain optical alignment. The optical alignment for the short-range overlap function is designed to minimize strong short-range signals, but the receiver will still saturate under the conditions of a strong signal (Wang et al. 2009). Very recent improvements in the WCL use two detectors for the parallel or perpendicular signals, increasing the dynamic range of the instrument. The WCL relies on a high-speed analog/digital (A/D) card to provide along-beam resolutions of 3.75 m or better. Resolution along the aircraft flight track (across beam) depends on the number of shots that must be averaged to achieve the desired signal-to-noise ratio, and typical values are 5–20 m. The WCL's first usable range gate is at about 30 m away from the aircraft. Wang et al. (2009) provide additional details about WCL-I and its measurement capabilities for clouds and aerosols.

The short operating wavelengths of the WCL allow detection of weak molecular and aerosol signals. For clouds, the WCL has considerably weaker dependence on particle size than the WCR. Therefore, in precipitating water clouds and in mixed-phase clouds, the WCL signal is often dominated by small cloud droplets. However, WCL signals can be quickly attenuated by optically thick water clouds. These characteristics of cloud signals from the WCL complement those of the WCR and offer improved cloud characterization capabilities by combining them (Wang and Sassen 2001, 2002; Wang et al. 2009).

G-band water vapor radiometer. A pod-mounted G-band water vapor radiometer (GVR) was developed by ProSensing, Inc. (Pazmany 2007). The installation on UWKA is shown in Fig. 1. The GVR measures brightness temperature using four double-sideband receiver channels, centered at 183.31 ±1, ±3, ±7, and ±14 GHz, at a rate of 24 Hz. Precipitable water vapor (PWV) and liquid water path (LWP) are estimated from the measured brightness temperatures and flight-level temperature based on a neural network trained with PWV and LWP computed from an atmospheric model generated using simulated liquid clouds combined with radiosonde data collected over a 7-yr period in Albany, New York (Pazmany 2007). Due to the high absorption rates of water vapor and liquid water near 183 GHz, the GVR has much greater sensitivity to detect LWP from aircraft or in cold regions than conventional microwave radiometers operating at 23 and 31 GHz. However, increased sensitivity comes at the cost of reduced dynamic range and at these high frequencies the receiver will saturate at lower water vapor contents leading to an inability to independently retrieve PWV and LWP in warm, high water content regions, such as the subtropics (Payne et al. 2011; Zuidema et al. 2011). PWV and LWP, combined with vertical resolved WCR and WCL measurements, are used to study the microphysical properties of mixed-phase and drizzling water clouds.

The first aircraft installation and testing of the GVR was on the National Research Council Canada (NRC) Convair 580 in 2007. Following that, the GVR was installed and tested on the UWKA for WAICO in early 2008. It was then installed on the NSF–NCAR C130 as part of VOCALS (Zuidema et al. 2011). Since VOCALS, this tested GVR is no longer available. However, the technology to build such an instrument still exists and the examples presented in the "Observation and retrieval samples" section highlight the utility of this instrument, particularly in concert with other remote sensors.

In situ cloud probes. The UWKA is designed to be a flexible and highly configurable platform depending on the mission objectives of a given project. The UWKA facility maintains a standard suite of instruments that are capable of providing size-resolved particle distributions from ~0.1 μm to several millimeters. The UWKA carries four wingtip-mount Particle Measuring Systems, Inc. (PMS), canisters for mounting many of the standard probes for in situ cloud physics measurements. The selection of specific probes depends on the measurement requirements of the program coupled with the power, space, and weight limitations dictated by the overall instrument package. "Standard" cloud physics instruments maintained by the facility include the PMS Forward Scattering Spectrometer Probe (FSSP), and optical array probe (OAP) 2D cloud (2DC) and 2D precipitation (2DP) probes (see Table 1), all of which are relatively well-characterized instruments with known limitations (Korolev et al. 2011). Recent additions to the instrument suite include the Droplet Measurement Technologies, Inc.'s (DMT's) cloud droplet probe (CDP; Lance et al. 2010), which replaces the FSSP with a much smaller and less power-consuming package that is much less susceptible to shattering contamination of measured particle size distributions. A *fast* OAP-2DC grayscale similar to the DMT cloud imaging probe (CIP), with 64 diodes and 25-μm-resolution duplicates, significantly improves upon the measurements provided by the standard 2DC. To complement the direct particle measurements, two additional instruments—the Gerber particle volume monitor (PVM) 100A (Gerber et al. 1994) and DMT liquid water concentration (LWC) 100—provide bulk measurements of cloud liquid water content, and the Rosemount ice detector provides icing rate and an additional estimate of supercooled cloud liquid water content.

Cloud microphysical measurements may be complemented by aerosol microphysical measurements with the TSI condensation particle counter (CPC) 3025 for ultrafine nuclei and the TSI CPC 3010 for condensation nuclei (CN). Both instruments provide total aerosol concentration for particles greater than 3 and 15 nm, respectively. Size-resolved aerosol distributions from 0.1 to about 3 μm are provided by a DMT passive cavity aerosol spectrometer probe (PCASP)-100.

In addition to facility-maintained instruments, the UWKA has extensive capability to integrate instruments belonging to outside groups. For example, a deep-cone Nevzorov probe (Korolev et al. 1998) was used to obtain redundant hotwire cloud LWC and IWC measurements in shallow, precipitating mixed-phase clouds. A closed-path laser hygrometer (CLH; Davis et al. 2007) was successfully used to retrieve total condensed water in ice clouds and mixed-phase clouds within orographic winter clouds. Probes capable of either using existing fuselage ports (for internal instruments) or existing PMS canisters are the simplest to accommodate.

As with all aircraft, the UWKA is limited by volume, weight, and power. Many additional in situ instruments that are available on larger aircraft are not available on the UWKA. For that reason, it was important to develop the remote sensing capability such that it could be transferred to other aircraft. As part of the NSF LAOF, the WCR and WCL can and have been mounted on the NSF–NCAR C130, a plane with significantly greater payload capacity and longer duration than the UWKA.

FIELD EXPERIMENTS. *WAICO experiment.* The WAICO experiment was conducted during February–March 2008 and 2009 in southeastern Wyoming. The objective of the study was to develop and demonstrate new cloud observation capabilities by first integrating remote sensors and in situ probes on the UWKA and, second, by obtaining measurements in mixed-phase clouds during late winter and early spring.

The first task is to meet the project objectives centered on installing the newly developed WCL and GVR with the WCR while maintaining a full complement of in situ probes. Successful integration of these instruments on the UWKA required novel solutions to minimize operating power requirements. During the WAICO experiments we were able to operate the WCR, WCL, and GVR with the Gerber PVM, FSSP, 2DC, and 2DP for cloud observations and the PCASP and CPC for aerosol size and concentration. Broadband radiation measurements were available from upward- and downward-looking pyranometers [Eppley precision spectral pyranometer (PSP), 0.29–2.8 μm], and pyrgeometers [Eppley precision infrared radiometer (PIR), 3.5–50 μm].

The second task was to collect data for the development and validation of combined WCR–WCL–GVR cloud retrieval algorithms. Modified versions of the ground-based multisensor algorithms created for airborne applications are required thorough validation. The WAICO flight patterns were developed and cloud targets were selected to collect proper data for this algorithm development and validation.

The third task was to collect data to study mixed-phase clouds. Compared to water- and ice-phase clouds, mixed-phase clouds are more complicated and their characteristics are less well quantified. During the WAICO experiments, we collected data from mixed-phase stratiform and wave clouds over a range of cloud temperatures and aerosol conditions.

VOCALS. VOCALS was conducted in fall 2008 off the coast of northern Chile over the northern extent of the South Pacific Ocean around 20°S latitude. VOCALS was a large, international effort to observe critical components of the coupled climate system of the South Pacific (Wood et al. 2011b). The NSF–NCAR C130 was one of five aircraft that were used to study the coupling of the chemistry, ocean, and clouds within the study area. The WCR, WCL-I, and GVR were installed on the C130 to complement the in situ measurements package for VOCALS (Zuidema et al. 2011). Cloud observations from VOCALS consisted entirely of liquid, marine stratocumulus in the subtropical boundary layer. The observations contained both precipitating (drizzle) and nonprecipitating clouds with generally low droplet concentrations. These conditions are a stark contrast to those from WAICO.

OBSERVATION AND RETRIEVAL EXAMPLES. Here we present examples from WAICO and VOCALS illustrating our new capabilities for observing clouds and for diagnosing processes occurring within them, that is, heterogeneous and homogeneous ice nucleation, drizzle, and cloud-scale dynamics. The first four examples focus on microphysics of cold clouds from WAICO. The fifth example illustrates use of a similar capability but for a marine stratocumulus cloud in VOCALS. The last example illustrates the capability of retrieving cloud dynamics properties from a WAICO case.

Wave cloud. With its relatively simple airflow structure (Heymsfield and Miloshevich 1993), wave clouds are one of the best natural targets for cloud microphysical processes study. Figure 2 presents data from a pair of wave clouds sampled during the WAICO experiment. The flight-level temperature is about −25°C. In the upwind region of the first wave (left side of Fig. 2), WCR Z_e is due to new ice formation with a gradual increase in response to growth of the ice crystals throughout the cloud. The Z_e is continuous from the descending part of the first wave to the inflow of the second due to ice particles that survive sublimation and enter the updraft of the second wave. High attenuation and weak depolarization of the lidar signal (Figs. 2b,c) just above flight level indicate that liquid droplets were present in the rising portions of the waves. Deeper penetration of the lidar beam and high depolarization ratios reveal where in the sinking portions of the waves the water droplets evaporated and only ice was present. In those regions, the ice water content can be retrieved from the combination of WCR and WCL signals (Deng et al. 2008).

At the flight level, 2DC and FSSP measurements (Figs. 2d,e) yield size distributions of ice crystals and water droplets. The size distributions of water droplets are quite narrow because of the short growth time available in the cloud. Ice particles were detected a little later than liquid droplets in the first wave. In the second wave ice is detected right from the moment of entering the second wave. These in situ details are consistent with the WCR and WCL measurements. The broad FSSP distributions that appear in the downwind tails of the waves are artifacts resulting from shattering of large ice particles (Korolev and Isaac 2005). The PCASP (Fig. 2f) provides aerosol size distributions outside of cloud to better link cloud and aerosol microphysical properties. However, the in-cloud PCASP measurements seen here seem to be affected by the presence of ice crystals and perhaps also by the detection of partially dried hydrometeors (Strapp et al. 1992).

The in situ vertical velocity and the deduced LWP shown in Fig. 2g confirm the relatively simple dynamic structure of the waves and show that the maximum in LWP coincides, as expected, with the crest of the wave. The lower LWP maximum in the second wave is associated with the higher ice concentration there and the greater vapor uptake by these crystals via the Bergeron–Findeisen process. Although there are many potential sources of uncertainties in GVR retrievals (Payne et al. 2011; Zuidema et al. 2011), the close-to-zero LWPs during liquid-free regions and relative variations of LWP in these wave clouds indicated that GVR LWP retrievals for these colder clouds are reliable.

Heterogeneous ice nucleation in wave clouds. Ice generation in clouds present a grand challenge to model cloud radiative impacts and precipitation formation. There are large uncertainties in parameterizing heterogeneous ice nucleation (DeMott et al. 2010). With the integrated airborne cloud observation capability, we offer new opportunities to study these phenomena.

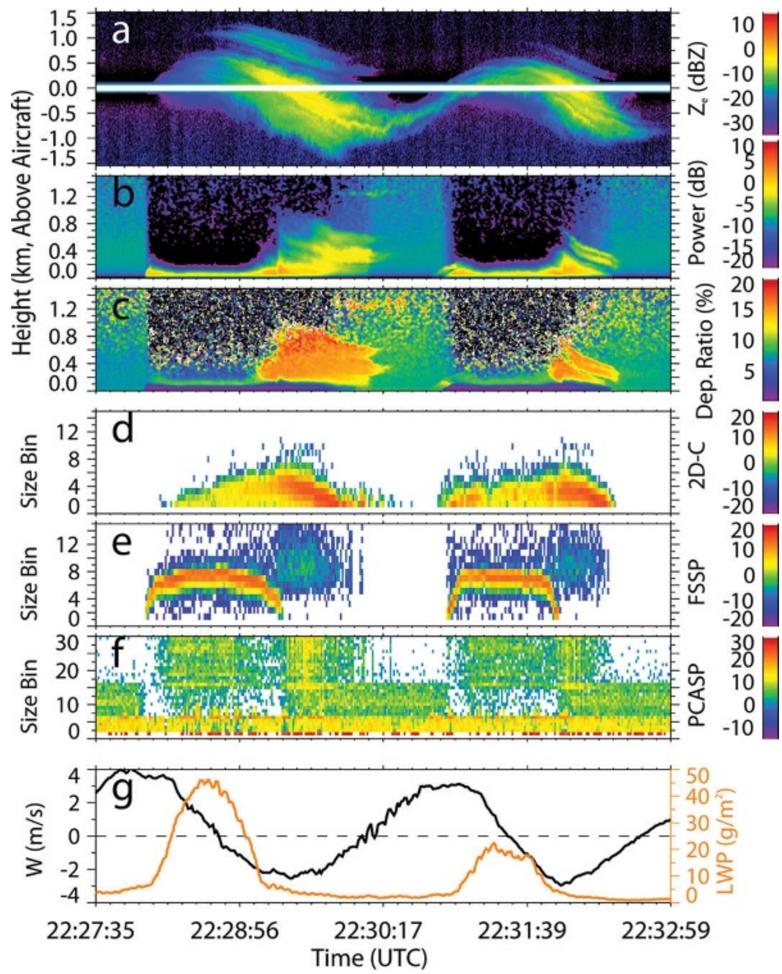


Fig. 2. A wave cloud train sampled by UWKA on 28 Feb 2008: (a) WCR radar reflectivity (the white gap indicates a zone near the aircraft without measurements), (b) WCL-I power, (c) WCL-I linear depolarization ratio (uncalibrated), (d) 2DC number concentration (*N*) for each bin [plotted as 10log(*N*)], (e) FSSP number concentration (*N*) for each bin [plotted as 10log(*N*)], (f) PCASP number concentration (*N*) for each bin [plotted as 10log(*N*)], and (g) air vertical velocity and GVR-derived LWP. The wind is blowing from left to right.

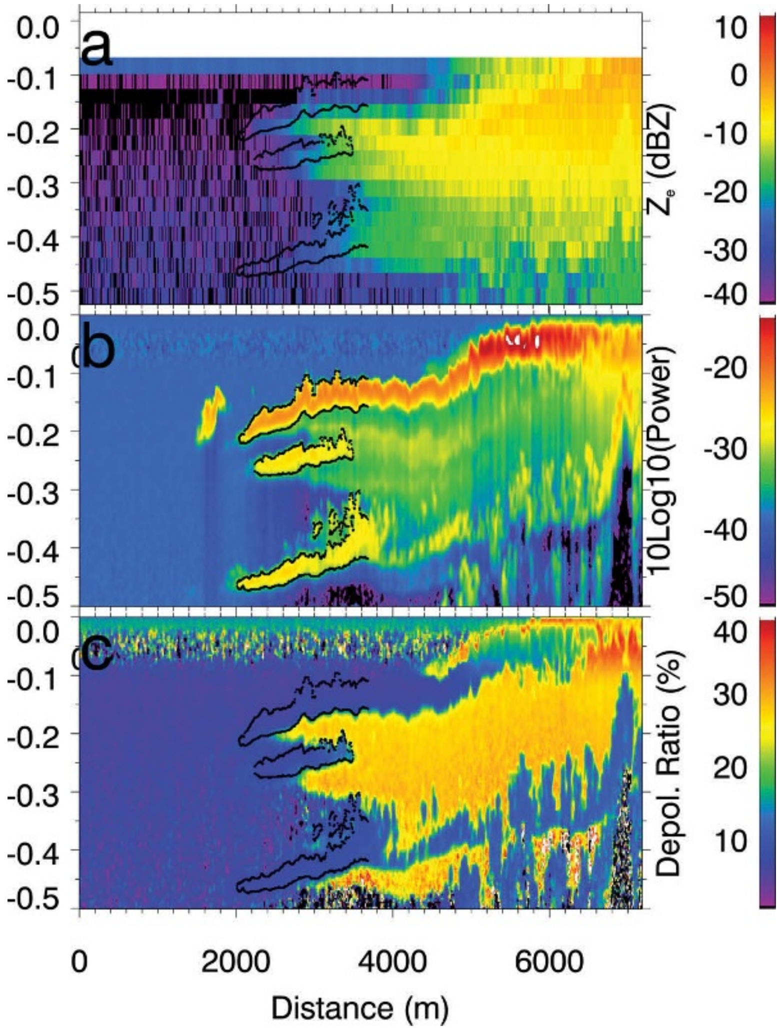


FIG. 3. WCR and WCL observations of ice formation in mixed-phase clouds on 8 Mar 2009: (a) WCR Z_e, (b) WCL-II power, and (c) WCL-II depolarization ratio (uncalibrated). The black contour outlines three distinct cloud layers; see the text for further explanation.

The rate of ice formation and its dependence on temperature in mixed-phase clouds is an especially perplexing problem. An example of its complexity and how it may be studied is illustrated in Fig. 3, showing multilayer orographically forced clouds. The black contours encompass three distinct regions of strong WCL power and low depolarization ratio outlining supercooled water-dominated mixed-phase layers, with the upwind side of the clouds on the left of figure. These three layers are separated by only 300 m and vary in temperature by only 2°C, with the uppermost layer at −31°C. The onset of WCL depolarization signal and increased WCR reflectivity provides a strong indication of the difference in location of the first onset of ice in these layers. Even with the small temperature difference between layers, ice is generated within about 200 m of the upwind edge in the uppermost cloud and more than 500 m in the lowermost cloud. Further, the stronger depolarization signal and WCR reflectivity from the higher clouds suggests greater ice number concentration at the slightly colder temperatures. These data are consistent with a steep rise in freezing rate as a function of temperature (e.g., Vali 1994, 2008). The real-time display of such finescale cloud vertical structure would allow investigators to better position aircraft for detailed in situ measurements of cloud microphysical and aerosol properties.

The synergy of in situ and remote sensing sampling within wave clouds provides a more complete picture of microphysical processes in these clouds and lessens the ambiguities resulting from in situ sampling alone. Combining the velocity information from in situ and Doppler data allows the determination of parcel trajectories through wave clouds. An example is shown in Fig. 4 (top panel) of two trajectories (solid red and dashed violet lines) overlain on the WCR Z_e cross section. For each trajectory the parcels were intercepted twice by the UWKA, on the upwind (left) and downwind (right) side of the wave at the zero level indicated in the top panel. The bottom left panel (Fig. 4b) shows ice crystal spectra for both trajectories on the upwind (solid) and downwind (dashed) side of the wave. Growth to larger sizes is evident, although it must be remembered that additional ice nucleation along the trajectory is expected as the parcel undergoes further cooling (bottom right panel, dashed lines) and as crystals fall into and out of the parcel. WCR Z_e along the trajectories is consistent with the continued ice generation and growth along the trajectory and can be used to provide additional information on these processes. The observed variation of Z_e along the parcel trajectory (bottom right panel) provides further information on the evolution of the crystal population. This case demonstrates how the combined in situ and remote sensing data provide insight, confirmation of expected results, and quantitative bases for model comparisons.

Homogeneous ice nucleation. Below approximately –35°C, pure supercooled water freezes without the aid of ice nuclei, but that simple fact is complicated by the presence of dissolved substances in high concentrations, which is the case with aerosol approaching water saturation. Although the freezing rate for homogeneous nucleation is well defined (Jeffery and Austin 1997; Pruppacher 1995) and it is generally considered to be simpler than heterogeneous ice nucleation (Cantrell and Heymsfield 2005), predicting ice number concentration generated from the homogeneous nucleation has large differences among different approaches (Lin et al. 2002; Liu and Penner 2005; Sassen and Benson 2000; Karcher and Lohmann 2003; Barahona and Nenes 2008). Field observations of homogeneous ice nucleation under different aerosol and dynamics conditions are needed to improve our capability to reliably simulate this process.

Figure 5 shows a case of homogeneous ice nucleation in a wave cloud observed on 16 March 2009. Flight-level temperature was about –41°C. In this case WCR Z_e is much weaker and increases more slowly through the cloud than in previous examples because of much smaller ice crystals. Backscatter from the WCL reveals strong attenuation throughout the cloud and the WCR

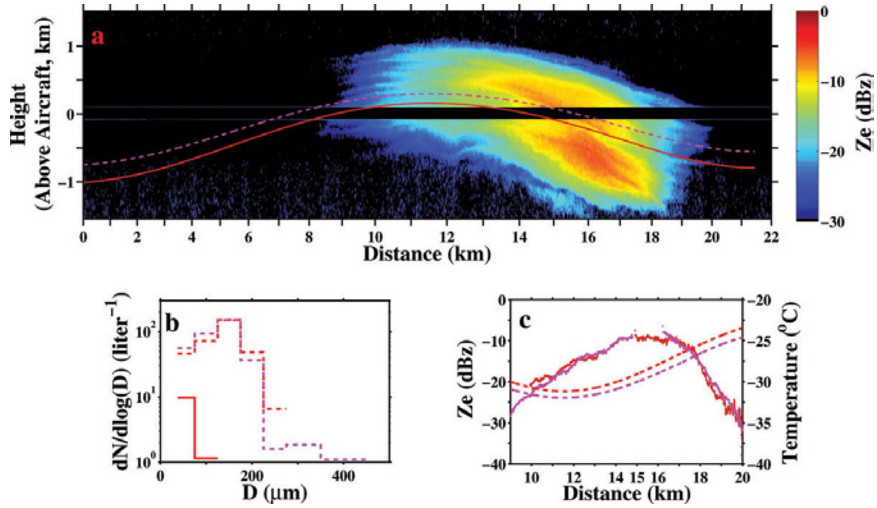


Fig. 4. Cloud and air property variations along stream lines: (a) two parcel trajectories overlaid on WCR Z_e vertical cross section, (b) ice size distributions intercepted at the flight level for the upwind (solid) and downwind (dashed) side of the cloud, and (c) air parcel temperature and Z_e along the trajectories.

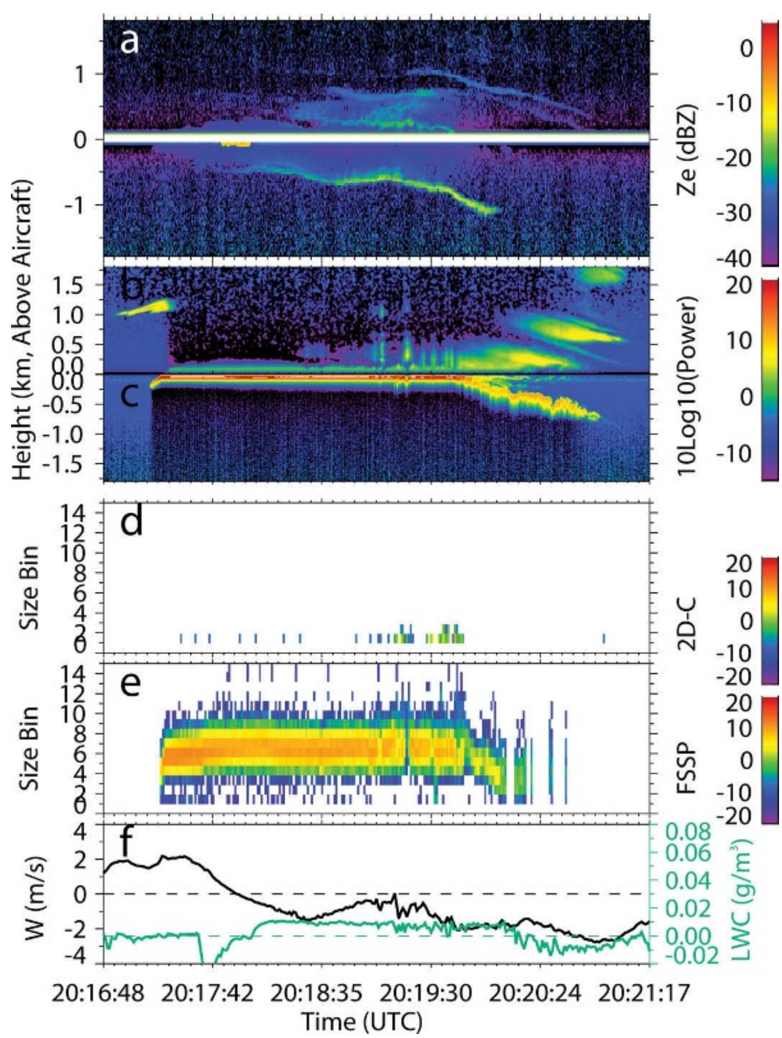


Fig. 5. A wave cloud with homogeneous ice nucleation observed on 16 Mar 2009: (a) WCR Z_e, (b),(c) up and down WCL returned power, (d) 2DC number concentration (*N*) [per bin in 10log(*N*)], (e) FSSP number concentration (*N*) [per bin in 10log(*N*)], and (f) vertical velocity (left y axis) and LWC from the hotwire probe (right y axis).

and WCL signals first appear at the same location within the cloud. These combined measurements are consistent with large numbers of very small ice crystals. The 2DC probe detected very few ice crystals. The FSSP suggests high numbers (up to 30 cm^{-3}) of small particles, but quantitative interpretation of the FSSP spectra for ice crystals is unreliable because of differences in the index of refraction of water and ice, although the total number concentration should be correct. The hotwire LWC signal is not significantly different from the clear-air noise value, confirming that very little or no liquid was present. An interesting feature of this case is the presence of narrow bands of strong WCR reflectivity. These bands occur at different temperatures and reveal some nonunderstood factors in homogeneous or heterogeneous ice nucleation in natural clouds. Further examinations of such data on homogeneous ice nucleation may open the way to improvements in its parameterization in models.

Aircraft-produced ice particles. Adiabatic expansion and the resulting cooling near the ends of propeller blades can, under the right conditions, lead to the homogeneous freezing of supercooled water in clouds. Thus, turboprop aircraft, such as the UWKA and the NSF–NCAR C130, can produce aircraft-produced ice particles (APIPs). Scientists utilizing aircraft for studies of cold processes must be cognizant of this and develop flight patterns to avoid biasing their results because of "artificially" produced ice. Woodley et al. (2003) speculate that APIPs led investigators to overestimate the development and concentrations of ice particles in clouds.

Figure 6 presents a case in which APIPs are identified from remote sensing and in situ measurements. The aircraft pass shown in the figure was along the wind (from left to right) and was preceded by another in the opposite direction by about 2 min and 150 m higher up. As seen in Fig. 6, the generally smooth Z_e structure of typical wave clouds is punctuated by patches of higher reflectivity in a pattern that is consistent with having been generated along the previous penetration. One of the high Z_e patches was sampled with the UWKA slightly after 2003 UTC. There is a significant local jump in ice concentration (2DC data) and a corresponding decrease in cloud water (FSSP data). At the same time, the CN counter shows an order of magnitude increase in aerosol concentration. These are all consistent with the generation of APIPs during the earlier pass. Clearly, such studies can lead to fuller understanding of the process of APIPs generation and of its consequences.

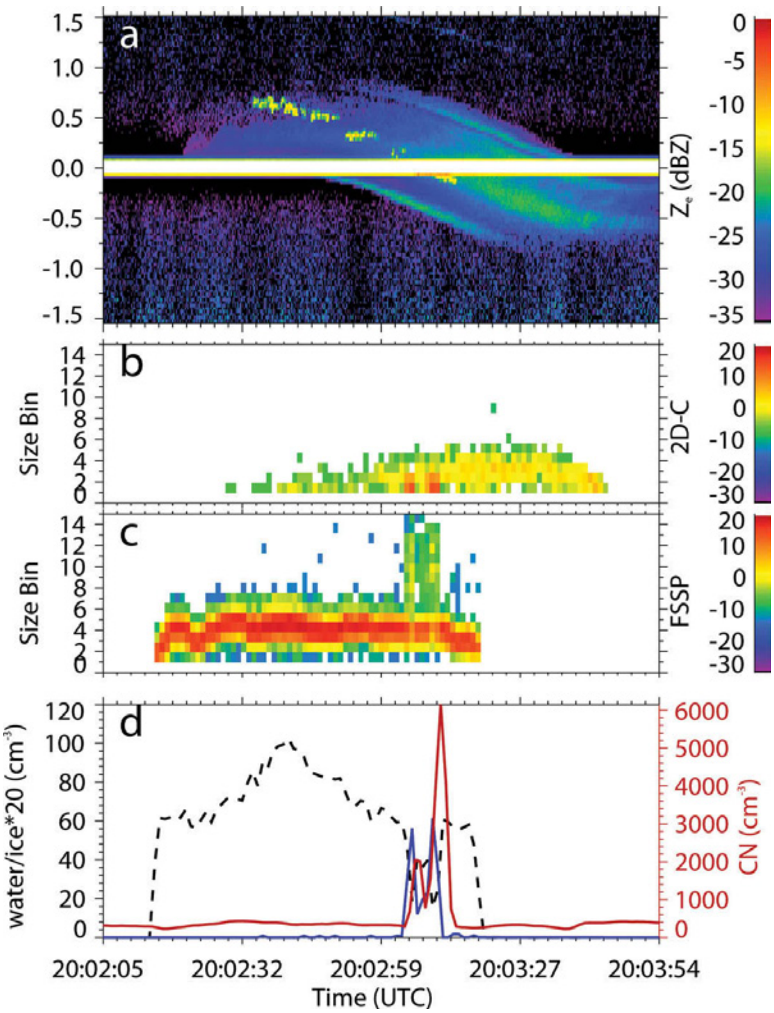


FIG. 6. An example of APIP observed in a wave cloud on 27 Feb 2008: (a) WCR Z_e, (b) 2DC number concentration (*N*) [per bin in 10log(*N*)], (c) FSSP number concentration (*N*) [per bin in 10log(*N*)], (d) water droplet (dashed line) and ice (solid line, x20) concentration (left y axis) and CN concentration (right y axis). The flight-level temperature is ~ −25°C.

Cloud microphysical property retrievals. The synergy of multiple remote sensor airborne measurements allows for improved cloud microphysical property retrievals by using

TABLE 3. A list of measurements needed to retrieve ice-, water-, and mixed-phase cloud microphysical properties.

Measurements	Ice clouds	Water clouds	Mixed-phase clouds
	IWC and D_{ge}	LWC , r_{eff} , and drizzle property	IWC and D_{ge} for ice phase LWC and r_{eff} for water phase
WCL	Extinction	Extinction	Extinction depolarization ratio
WCR	Z_e	Z_e	Z_e or spectrum
GVR		LWP	LWP
References	Donovan and van Lammeren (2001), Wang and Sassen (2002), Heymsfield et al. (2008), Deng et al. (2010)	Frisch et al. (1995), Sassen et al. (1999), O'Connor et al. (2005), Wang (2007)	Wang et al. (2004) and Shupe et al. (2008)

approaches similar to those developed for ground-based measurements. Table 3 lists the WCR, WCL, and GVR measurements needed for retrievals of water, mixed-phase, and ice cloud microphysical properties and the related published ground-based and satellite retrieval algorithms. Because ice clouds are optically thin compared with water and mixed-phase clouds, combined WCL and WCR measurements can be used to retrieve the vertical profiles of IWC and general effective radius (D_{ge}). As confirmed by Heymsfield et al. (2008), these lidar–radar approaches can yield reliable estimates of ice bulk properties. Several ground- and satellite-based approaches can be easily modified for airborne applications. Wang et al. (2009) present an example of retrievals of ice cloud microphysical properties using WCL and WCR measurements and illustrate the advantages of evaluating the retrieved parameters based on combined airborne measurements.

For stratiform water clouds without drizzle, combined WCR Z_e profiles and GVR LWP measurements are enough to provide water cloud properties (Frisch et al. 1995, 1998; Sassen et al. 1999). However, in the presence of drizzle, the drizzle drops dominate the signal from the WCR (Fig. 7a) and also contribute to LWP (Vali et al. 1995). In this

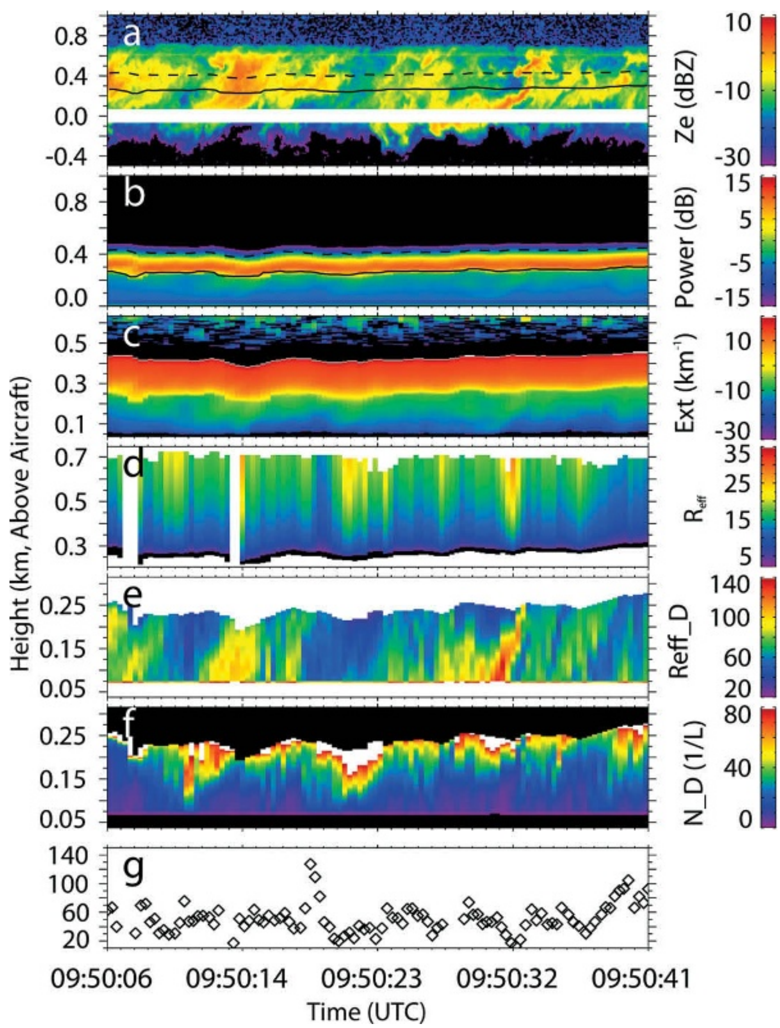


FIG. 7. WCR and WCL observations of drizzling stratocumulus clouds on 28 Oct 2008 during the VOCALS field campaign: (a) WCR Z_e, (b) WCL attenuated backscatter power, (c) retrieved visible extinction coefficient, (d) cloud effective radius (μm) above cloud base, (e) drizzle effective radius (μm) below cloud base, (f) drizzle number concentration below cloud base, and (g) layer mean cloud droplet number concentration. In (a) and (b), the WCL-identified cloud base (solid lines) and the top of useable WCL data (dashed lines) are represented.

case, we must include WCL measurements and/or additional assumptions (such as adiabatic clouds) to retrieve water droplet as well as drizzle properties. Figures 7b,c illustrate how the WCL provides strong signals for easily identifying the cloud base from using the slope change of the backscattered power and extinction (Wang and Sassen 2001). WCL signals are attenuated within about 200 m of the cloud base; estimates of cloud-top height are provided by the WCR.

Many observations have shown that adiabatic ascent of cloud parcels is a reasonable assumption for most stratiform warm clouds, especially at small spatial scales and within the lower parts of clouds (Albrecht et al. 1990; Zuidema et al. 2005; Korolev et al. 2007), although some uncertainty remains because of our inability to accurately measure temperature within cloud (Heymsfield et al. 1979). With in situ measurements obtained not far below the cloud base, the cloud-base temperature can be reliably estimated and used to estimate an adiabatic LWC profile within about 300 m above the cloud base. With the assumption of lognormal size distribution of constant width, the lidar-derived cloud extinction profiles were combined with LWC profiles to derive mean cloud number concentration and effective radius profiles (Frisch et al. 1995); the retrieved r_{eff} profiles and mean droplet concentration are presented in Figs. 7d,g. Drizzle properties were derived from the WCR and WCL measurements below the cloud base (O'Connor et al. 2005); the retrieved drizzle effective radius and total concentration are presented in Figs. 7e,f.

Stratiform mixed-phase clouds and drizzling stratocumulus have similar vertical structures (Wang et al. 2004). A combination of WCL and GVR measurements of LWP can be used to characterize supercooled water cloud properties. Combining WCR and WCL below the mixed-phase layer can be used to derive ice-phase properties.

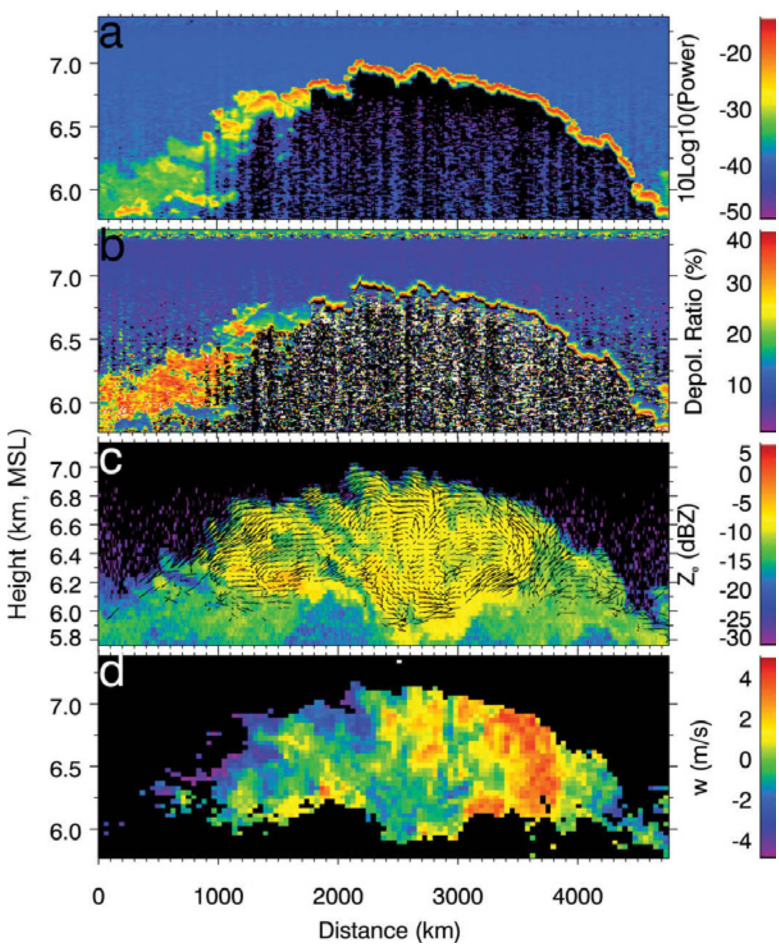


Fig. 8. WCL (a) backscattered power and (b) depolarization ratio from an orographically induced convective cloud. Resultant wind vectors (mean wind has been removed) retrieved from a dual-Doppler synthesis and overlain on the (c) WCR Z_e field and (d) retrieved vertical wind velocity for the same convective cloud.

Cloud dynamics retrievals. The dual-Doppler capability of the WCR provides a unique tool for the study of interactions between cloud-scale dynamics and cloud microphysics. WCR dual-Doppler measurements have been used to investigate cloud-scale dynamics in marine stratocumulus (Leon et al. 2006) and in much more vigorous cumulus congestus (Damiani et al. 2006). Figure 8 presents a similar analysis (Damiani and Haimov 2006) of an orographically forced convective cloud. Although WCL-II signals are quickly attenuated by supercooled water on the upwind side (right), the lidar data show the upper-cloud boundary and glaciation in the downwind side (left) well. The WCR measurements show details of the spatial variation of Z_e throughout the depth of the cloud. Dual-Doppler retrievals of 2D winds (Figs. 8c,d; 15 m s^{-1} mean horizontal wind is removed from the plot) reveal dominant upward motion on the upwind side and complex circulations on the downwind side. By overlaying the wind vectors on Z_e (contributed mostly by ice crystals), the relationship between the cloud-scale dynamics and precipitation development is depicted.

SUMMARY. The examples presented here demonstrate successful integration of the WCR, WCL, GVR, and the in situ cloud physics and aerosol probes on the UWKA and their use on other aircraft, the NSF–NCAR C130. Combined analyses of the multiple remote sensor and detailed microphysical measurements lead to better insights of key processes within clouds. We have shown that the remote sensing measurements provide important context for interpretation of the microphysics measurements and extend microphysics measurements away from the aircraft and along trajectories for interpreting the evolution of hydrometeors within clouds. Because the different remote sensors have different sensitivities to particles of different sizes, shapes, and phases, the radar–lidar–radiometer package provides better diagnoses of physical processes occurring in clouds than can be determined through in situ measurements alone or with just one of these remote sensors.

Algorithm development and validation for cloud macrophysical properties continues. Cases presented here highlight present capabilities for warm and cold clouds. Algorithms developed for ground-based and/or satellite-based schemes can be adopted to the airborne instrument suite and the addition of in situ measurements provides additional constraints for refinements of these algorithms for a variety of conditions.

Since the first WAICO campaign in the winter of 2008, the integrated cloud remote sensing platform has been used in six field campaigns, ranging from winter orographically forced clouds in the intemountain west to summer deep tropical convection. The WCR and both WCLs, supported through the NSF-funded LAOF, have been migrated to and are also available on the NSF–NCAR C130. That platform provides opportunities for other flight missions and has the capacity for significantly more and a broader range of in situ measurements. In the meantime, further development continues on the UWKA. With new instruments that are smaller and require less power, the UWKA continues to improve its in situ cloud microphysics measurements. Expansions of the real-time data display capabilities will allow scientists to utilize more information in making decisions on how best to position the aircraft and optimize the observations.

ACKNOWLEDGMENTS. This research is supported by NSF under Award AGS-0645644 and partially under Awards AGS-0650609, AGS-0745986, AGS-0964184, and AGS-1034858, and by the University of Wyoming. The UWKA is supported by NSF Award AGS-0334908. We would like to thank Drs. A. Detwiler, A. Heymsfield, B. Smull, T. Deshler, and C. Lu for their guidance, and to thank the UWKA and NSF–NCAR C-130 facility team for their efforts in collecting data, and to thank two reviewers for their helpful comments.

REFERENCES

Albrecht, B. A., C. Fairall, D. Thomson, A. White, and J. Snider, 1990: Surface-based remote sensing of the observed and the adiabatic liquid water content. *Geophys. Res. Lett.,* **17,** 89–92.

Bailey, M. P., and J. Hallett, 2009: A comprehensive habit diagram for atmospheric ice crystals: Confirmation from the laboratory, AIRS II, and other field studies. *J. Atmos. Sci.,* **66,** 2888–2899.

Baker, B. A., and R. P. Lawson, 2006: In situ observations of the microphysical properties of wave, cirrus, and anvil clouds. Part I: Wave clouds. *J. Atmos. Sci.,* **63,** 3160–3185.

Barahona, D., and A. Nenes, 2008: Parameterization of cirrus cloud formation in large-scale models: Homogeneous nucleation. *J. Geophys. Res.,* **113,** D11211, doi:10.1029/2007JD009355.

Cantrell, W., and A. J. Heymsfield, 2005: Production of ice in tropospheric clouds: A review. *Bull. Amer. Meteor. Soc.,* **86,** 795–807.

Damiani, R., and S. Haimov, 2006: A high resolution dual-Doppler technique for fixed multiantenna airborne radar. *IEEE Trans. Geosci. Remote Sens.,* **44,** 3475–3489.

——, G. Vali, and S. Haimov, 2006: The structure of thermals in cumulus from airborne dual-Doppler radar observations. *J. Atmos. Sci.,* **63,** 1432–1450.

Davis, S., A. G. Hallar, and L. Avallone, 2007: Measurement of total water with a tunable diode laser hygrometer: Inlet analysis, calibration procedure, and ice water content determination. *J. Atmos. Oceanic Technol.,* **24,** 463–475.

DeMott, P. J., and Coauthors, 2010: Predicting global atmospheric ice nuclei distributions and their impacts on climate. *Proc. Natl. Acad. Sci. USA,* **107,** 11 217–11 222, doi:10.1073/pnas.0910818107.

Deng, M., Z. Wang, G. Vali, S. Haimov, and J. French, 2008: Wave cloud properties observed from Wyoming cloud lidar and radar during the ICE-L field campaign. *Proc. 24th Int. Laser Radar Conf.,* Boulder, CO, International Coordination Group on Laser Atmospheric Studies (ICLAS), 917–920.

——, G. G. Mace, Z. Wang, and H. Okamoto, 2010: Tropical Composition, Cloud and Climate

Coupling Experiment validation for cirrus cloud profiling retrieval using CloudSat radar and CALIPSO lidar. *J. Geophys. Res.,* **115,** D00J15, doi:10.1029/2009JD013104.

Donovan, D. P., and A. C. A. P. van Lammeren, 2001: Cloud effective particle size and water content profile retrievals using combined lidar and radar observations—1. Theory and examples. *J. Geophys. Res.,* **106,** 27 425–27 448.

French, J., G. Vali, and R. D. Kelly, 1999: Evolution of small cumulus clouds in Florida: Observations of pulsating growth. *Atmos. Res.,* **52,** 143–165.

——, ——, and ——, 2000: Observations of microphysics pertaining to the development of drizzle in warm, shallow cumulus clouds. *Quart. J. Roy. Meteor. Soc.,* **126,** 415–443.

Fritsch, J. M., and R. E. Carbone, 2004: Improving quantitative precipitation forecasts in the warm season: A USWRP research and development strategy. *Bull. Amer. Meteor. Soc.,* **85,** 955–965.

——, C. W. Fairall, and J. B. Snider, 1995: Measurement of stratus cloud and drizzle parameters in ASTEX with a K_e-band Doppler radar and a microwave radiometer. *J. Atmos. Sci.,* **52,** 2788–2799.

——, G. Feingold, C. W. Fairall, T. Uttal, and J. B. Snider, 1998: On cloud radar and microwave radiometer measurements of stratus cloud liquid water profiles. *J. Geophys. Res.,* **103,** 23 195–23 197.

Galloway, J., and Coauthors, 1999: Coincident in situ and W-band radar measurements of drop size distribution in a marine stratus cloud and drizzle. *J. Atmos. Oceanic Technol.,* **16,** 504–517.

Gerber, H., B. G. Arends, and A. S. Ackerman, 1994: New microphysics sensor for aircraft use. *Atmos. Res.,* **31,** 235–252.

Gordon, G. L., and J. D. Marwitz, 1984: An airborne comparison of three PMS probes. *J. Atmos. Oceanic Technol.,* **1,** 22–27.

Heymsfield, A. J., and L. M. Miloshevich, 1993: Homogeneous ice nucleation and supercooled liquid water in orographic wave clouds. *J. Atmos. Sci.,* **50,** 2235–2353.

——, J. E. Dye, and C. J. Biter, 1979: Overestimates of entrainment from wetting of aircraft temperature sensors in cloud. *J. Appl. Meteor.,* **18,** 92–95.

——, and Coauthors, 2008: Testing IWC retrieval methods using radar and ancillary measurements with in situ data. *J. Appl. Meteor. Climatol.,* **47,** 135–163.

Heymsfield, G. M., and Coauthors, 1996: The EDOP radar system on the high-altitude NASA ER-2 aircraft. *J. Atmos. Oceanic Technol.,* **13,** 795–809.

Hildebrand, P. H., and Coauthors, 1996: The ELDORA/ASTRAIA airborne Doppler weather radar: High-resolution observations from TOGA COARE. *Bull. Amer. Meteor. Soc.,* **77,** 213–232.

Isaac, G. A., and K. S. Schmidt, 2009: Cloud properties from in-situ and remote sensing measurements, capability and limitations. *Clouds in the Perturbed Climate System,* J. Heintzenberg and R. J. Charlson, Eds., The MIT Press, 73–106.

Jeffery, C., and P. Austin, 1997: Homogeneous nucleation of supercooled water: Results from a new equation of state. *J. Geophys. Res.,* **102,** 25 269–25 279.

Karcher, B., and U. Lohmann, 2003: A parameterization of cirrus cloud formation: Heterogeneous freezing. *J. Geophys. Res.,* **108,** 4402, doi:10.1029/2002JD003220.

Klein, S. A., and Coauthors, 2009: Intercomparison of model simulations of mixed phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. Part I: Single-layer cloud. *Quart. J. Roy. Meteor. Soc.,* **135,** 979–1002, doi:10.1002/qj.416.

Korolev, A. V., and G. A. Isaac, 2005: Shattering during sampling by OAPS and HVPS. Part I: Snow particles. *J. Atmos. Oceanic Technol.,* **22,** 528–542.

——, J. W. Strapp, G. A. Isaac, and A. N. Nevzorov, 1998: The Nevzorov airborne hot-wire LWC–TWC probe: Principle of operation and performance characteristics. *J. Atmos. Oceanic Technol.,* **15,** 1495–1510.

——, G. A. Isaac, J. W. Strapp, S. G. Cober, and H. W. Barker, 2007: In situ measurements of liquid water content profiles in midlatitude stratiform clouds. *Quart. J. Roy. Meteor. Soc.,* **133,** 1693–1699.

——, E. F. Emery, J. W. Strapp, S. G. Cober, G. A. Isaac, M. Wasey, and D. Marcotte, 2011: Small ice particles in tropospheric clouds: Fact or artifact? Airborne Icing Instrumentation Evaluation Experiment. *Bull. Amer. Meteor. Soc.,* **92**, 967–973.

Lance, S., C. A. Brock, D. Rogers, and J. A. Gordon, 2010: Water droplet calibration of the cloud droplet probe and in-flight performance in liquid, ice and mixed-phase clouds during ARCPAC. *Atmos. Meas. Tech.,* **3,** 1683–1706.

Leon, D., G. Vali, and M. Lothon, 2006: Dual-Doppler analysis in a single plane from an airborne platform. Part I: Technique. *J. Atmos. Oceanic Technol.,* **23,** 3–21.

Lin, R., D. Starr, P. J. DeMott, R. Cotton, K. Sassen, E. J. Jensen, B. Kärcher, and X. Liu, 2002: Cirrus parcel model comparison project. Phase I: The critical components to simulate cirrus initiation explicitly. *J. Atmos. Sci.,* **59,** 2305–2328.

Liu, X., and J. E. Penner, 2005: Ice nucleation parameterization for global models. *Meteor. Z.,* **14,** 499–514.

McFarquhar, G. M., G. Zhang, M. R. Poellot, G. L. Kok, R. McCoy, T. Tooman, A. Fridlind, and A. J. Heymsfield, 2007: Ice properties of single-layer stratocumulus during the Mixed-Phase Arctic Cloud Experiment: 1. Observations. *J. Geophys. Res.,* **112,** D24201, doi:10.1029/2007JD008633.

McGill, M. J., D. L. Hlavka, W. D. Hart, J. D. Spinhirne, V. S. Scott, and B. Schmid, 2002: The cloud physics lidar: Instrument description and initial measurement results. *Appl. Opt.,* **41,** 3725–3734.

NRC, 1998: *The Atmospheric Sciences Entering the Twenty-First Century*. National Academy Press, 384 pp.

O'Connor, E. J., R. J. Hogan, and A. J. Illingworth, 2005: Retrieving stratocumulus drizzle parameters using Doppler radar and lidar. *J. Appl. Meteor.,* **44,** 14–27.

Payne, V. H., E. J. Mlawer, K. E. Cady-Pereira, and J. Moncet, 2011: Water vapor continuum absorption in the microwave. *IEEE Trans. Geosci. Remote Sens.,* **49,** 2194–2208.

Pazmany, A. L., 2007: A compact 183-GHz radiometer for water vapor and liquid water sensing. *IEEE Trans. Geosci. Remote Sens.,* **45,** 2202–2206.

Pratt, K. A., and Coauthors, 2009: In situ detection of biological particles in cloud ice-crystals. *Nat. Geosci.,* **2,** 398–401, doi:10.1038/ngeo521.

Pruppacher, H., 1995: A new look at homogeneous ice nucleation in supercooled water drops. *J. Atmos. Sci.,* **52,** 1924–1933.

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski, 2003: Breaking the cloud parameterization deadlock. *Bull. Amer. Meteor. Soc.,* **84,** 1547–1564.

Rangno, A. L., and P. V. Hobbs, 1991: Ice particle concentrations and precipitation development in small polar maritime cumuliform clouds. *Quart. J. Roy. Meteor. Soc.,* **117,** 207–241.

——, and ——, 2001: Ice particles in stratiform clouds in the arctic and possible mechanisms for the production of high ice concentrations. *J. Geophys. Res.,* **106,** 15 065–15 075.

Rodi, A., 2011: King of the air: The evolution and capabilities of Wyoming's observation aircraft. *Meteorological Technology International,* May 2011, UKIP, 44–47.

Sassen, K., and S. Benson, 2000: Ice nucleation in cirrus clouds: A model study of the homogeneous and heterogeneous modes. *Geophys. Res. Lett.,* **27,** 521–524.

——, G. G. Mace, Z. Wang, S. M. Sekelsky, and R. E. McIntosh, 1999: Continental stratus clouds: A case study using coordinated remote sensing and aircraft measurements. *J. Atmos. Sci.,* **56,** 2345–2358.

Shupe, M. D., and Coauthors, 2008: A focus on mixed-phase clouds: The status of ground-based observational methods. *Bull. Amer. Meteor. Soc.,* **89,** 1549–1562.

Snider, J. R., and M. D. Petters, 2008: Optical particle counter measurement of marine aerosol hygroscopic growth. *Atmos. Chem. Phys.,* **8,** 1949–1962.

Soden, B. J., and I. M. Held, 2006: An assessment of climate feedbacks in coupled ocean–atmosphere models. *J. Climate,* **19,** 3354–3360.

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

Stephens, G. L., and Coauthors, 2002: The CloudSat mission and the A-Train: A new dimension to space-based observations of clouds and precipitation. *Bull. Amer. Meteor. Soc.,* **83,** 1771–1790.

Stevens, B., and Coauthors, 2003: Dynamics and Chemistry of Marine Stratocumulus—DYCOMS-II. *Bull. Amer. Meteor. Soc.,* **84,** 579–593.

Stoelinga, M. T., and Coauthors, 2003: Improvement of microphysical parameterization through observational verification experiment. *Bull. Amer. Meteor. Soc.,* **84,** 1807–1826.

Strapp, J. W., W. R. Leaitch, and P. S. K. Liu, 1992: Hydrated and dried aerosol-size-distribution measurements from Particle Measuring Systems FSSP-300 probe and deiced PCASP-100x probe. *J. Atmos. Oceanic Technol.,* **9,** 548–555.

Vali, G., 1994: Freezing rate due to heterogeneous nucleation. *J. Atmos. Sci.,* **51,** 1843–1856.

——, 2008: Repeatability and randomness in heterogeneous freezing nucleation. *Atmos. Chem. Phys.,* **8,** 5017–5031.

——, R. D. Kelly, A. Pazmany, and R. E. McIntosh, 1995: Airborne radar and in-situ observations of a shallow stratus with drizzle. *Atmos. Res.,* **38,** 361–380.

——, ——, J. French, S. Haimov, D. Leon, R. McIntosh, and A. Pazmany, 1998: Finescale structure and microphysics of coastal stratus. *J. Atmos. Sci.,* **55,** 3540–3563.

Wang, Z., 2007: A refined two-channel microwave radiometer liquid water path retrieval for cold regions by using multiple-sensor measurements. *IEEE Geosci. Remote Sens. Lett.,* **4,** 591–595.

——, and K. Sassen, 2001: Cloud type and macrophysical property retrieval using multiple remote sensors. *J. Appl. Meteor.,* **40,** 1665–1682.

——, and ——, 2002: Cirrus cloud microphysical property retrieval using lidar and radar measurements. Part I: Algorithm description and comparison with in situ data. *J. Appl. Meteor.,* **41,** 218–229.

——, ——, D. Whiteman, and B. Demoz, 2004: Studying altocumulus plus virga with ground-based active and passive remote sensors. *J. Appl. Meteor.*, **43,** 449–460.

——, G. M. Heymsfield, L. Li, and A. J. Heymsfield, 2005: Retrieving optically thick ice cloud microphysical properties by using airborne dual-wavelength radar measurements. *J. Geophys. Res.*, **110,** D19201, doi:10.1029/2005JD005969.

——, P. Wechsler, W. Kuestner, J. French, A. Rodi, B. Glover, M. Burkhart, and D. Lukens, 2009: Wyoming cloud lidar: Instrument description and applications. *Opt. Express,* **17,** 13 576–13 587.

Wood, R., C. S. Bretherton, D. Leon, A. D. Clarke, P. Zuidema, G. Allen, and H. Coe, 2011a: An aircraft case study of the spatial transition from closed to open mesoscale cellular convection. *Atmos. Chem. Phys.*, **11,** 2341–2370.

——, and Coauthors, 2011b: The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx): Goals, platforms, and field operations. *Atmos. Chem. Phys.*, **11,** 628–654, doi:10.5194/acp-11-627-2011.

Woodley, W. L., G. Gordon, T. J. Hendereson, B. Vonnegut, D. Rosenfeld, and A. Detwiler, 2003: Aircraft-produced ice particles (APIPS): Additional results and further insights. *J. Appl. Meteor.*, **42,** 640–651.

Zuidema, P., E. R. Westwater, C. Fairall, and D. Hazen, 2005: Ship-based liquid water path estimates in marine stratocumulus. *J. Geophys. Res.*, **110,** D20206, doi:10.1029/2005JD005833.

——, D. Leon, A. Pazmany, and M. Cadeddu, 2011: Aircraft millimeter-wave retrievals of cloud liquid water path during VOCALS-REx. *Atmos. Chem. Phys. Discuss.*, **11,** 19 581–19 616, doi:10.5194/acpd-11-19581-2011.

PARTLY CLOUDY WITH A CHANCE OF MIGRATION

Weather, Radars, and Aeroecology

BY PHILLIP B. CHILSON, WINIFRED F. FRICK, JEFFREY F. KELLY, KENNETH W. HOWARD, RONALD P. LARKIN, ROBERT H. DIEHL, JOHN K. WESTBROOK, T. ADAM KELLY, AND THOMAS H. KUNZ

Radar observations provide a valuable means of investigating questions about ecology, abundance, and airborne movement of animals over large spatial and temporal domains, and play an important role in the transdisciplinary field of aeroecology.

An initial surge in developing radar technology occurred before and during World War II in response to the need for an improved method of detecting and tracking positions of enemy aircraft (Buderi 1998). It was rapidly discovered that radar systems offered a wide range of applications beyond air defense. For example, while engaged in the early testing of military radar, researchers began to observe backscattered signals associated with regions of precipitation (Doviak and Zrnić 1993). Moreover, there was a noticeable correlation between the power of the backscatter to the intensity and the type of precipitation. Today radars play a vital role in meteorology and weather forecasting.

It was also during the early phases of radar development that scientists reported that some radio wave scatter could be attributed to the presence of airborne animals, such as birds, bats, and arthropods. Here, we refer to this broad category of radio wave scatter as "biological scatter" or bioscatter. The earliest account in the open scientific literature of radar being used to observe bioscatter is found in Lack and Varley (1945). Thus, it has been known for more than 60 years that radar can be used to study the behavior of flying, or volant, animals in the planetary boundary layer and lower free atmosphere (i.e., the aerosphere). A brief historical account can be found in Gauthreaux (2006).

Radar has been thoroughly integrated into research and operational meteorology; however, the same cannot be said for biology. That is not to say that radar has not been incorporated into biological research. There have been significant advancements in ornithology and entomology as a result of radar

AFFILIATIONS: CHILSON AND J. F. KELLY—University of Oklahoma, Norman, Oklahoma; FRICK—University of California, Santa Cruz, Santa Cruz, California; HOWARD—National Oceanic and Atmospheric Administration, Norman, Oklahoma; LARKIN—Illinois Natural History Survey, Champaign, Illinois; DIEHL—Northern Rocky Mountain Science Center, U.S. Geological Survey, Bozeman, Montana; WESTBROOK—Agricultural Research Service, U.S. Department of Agriculture, College Station, Texas; T. A. KELLY—DeTect Inc., Panama City, Florida; KUNZ—Boston University, Boston, Massachusetts
CORRESPONDING AUTHOR: Phillip Chilson, School of Meteorology, and Atmospheric Radar Research Center, University of Oklahoma, 120 David L. Boren Blvd., Norman, OK 73072
E-mail: chilson@ou.edu

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-11-00099.1

In final form 7 November 2011

observations (e.g., Vaughn 1985; Reynolds 1988; Bruderer 1997a,b; Gauthreaux and Belser 2003; Diehl and Larkin 2005; Larkin 2005) and exciting discoveries continue to be made. Furthermore, radar observations have contributed extensively to the entomology of economically important pests and beneficial insects in North America, Europe, Africa, Australia, and Asia (Chapman et al. 2011). And operational radar has been used for flight safety warnings during periods of heavy bird migration (van Belle et al. 2007; Shamoun-Baranes et al. 2008). However, when one considers the vast networks of radars currently in operation around the world, it can be argued that this technology has been underutilized for ecological research.

Using radar to detect and characterize the presence and movements of bioscatter is an example of the emerging scientific discipline of aeroecology. The objective of aeroecology is to broaden our understanding about ecological patterns and processes that result from the behavior of organisms in the aerosphere. These patterns and processes are best investigated by integrating disciplines such as atmospheric science, Earth science, geography, ecology, computer science, computational biology, and engineering (Kunz et al. 2008). Monitoring and tracking airborne fauna successfully with radar requires expertise from many scientific disciplines, but especially from atmospheric science, computer science, and ecology. The convergence of these disciplines with a focus on "radar aeroecology" has significant potential for furthering scientific investigations on diverse research topics including daily and nightly dispersal, migratory patterns, foraging behavior, distribution and quantification of aerial biomass, aerial biodiversity, phenological patterns related to climatic variability (Kelly et al. 2012), and conservation biology.

Here, we explore the benefits and challenges of developing a cohesive radar aeroecology program within the United States targeted at observations of volant organisms over a variety of spatial and temporal scales. In particular, we focus on data collected using the network of U.S. National Weather Service (NWS) weather surveillance Doppler radars [Weather Surveillance Radar-1988 Doppler (WSR-88D)] collectively known as Next Generation Weather Radar (NEXRAD) (Serafin and Wilson 2000). The NEXRAD network is already being used by some for biological research (e.g., Gauthreaux and Belser 1998; Russell et al. 1998; Diehl et al. 2003; Kunz and Horn 2008; Bonter et al. 2009; O'Neal et al. 2010), and radar tutorials are available for biologists (Gauthreaux and Belser 2003; Diehl and Larkin 2005; Larkin 2005; Mead et al. 2010). Moreover, progress is being made in the deployment and use of operational weather radars for biological studies in other countries (e.g., Dokter et al. 2010).

Although the focus of the present discussion is on NEXRAD, other radar networks may also have valuable potential for biological research. The United States maintains and operates terminal Doppler weather radars, airport surveillance radars, and air route surveillance radars (Weber et al. 2007). These could be integrated into biological research (e.g., Leshem and Yom-Tov 1996, 1998). A comprehensive radar aeroecology program would be able to take advantage of existing infrastructure while leveraging the rich body of experience in radar technology. In fact, we contend that the collective body of NEXRAD observations stored as raw and processed data at the National Climatic Data Center already represents one of the largest biological data archives in the world. Here, we present some of the applications of radar to aeroecology, discuss some of the challenges associated with applying radar to study biological targets, and propose the development of a cohesive radar aeroecology program within the United States, targeted at understanding the movements of volant organisms over a range of spatial and temporal scales.

SIGNIFICANCE OF RADAR AEROECOLOGY.

As one specific case of how NEXRAD is being used to assist biologists, consider the observation of purple martins (*Progne subis*) reported in Russell et al. (1998). Purple martins are insectivorous birds that feed in flight during the day. They often congregate in large roosting colonies prior to and during migration. Using NEXRAD data, Russell et al. (1998) identified the locations of several martin roost sites, observed the daily behavior of these birds, and conducted a detailed investigation of daily movement patterns of martins from one particular roost in South Carolina. As martins disperse from their roosting site and begin foraging for food early in the morning, they produce a distinctive ring-shaped region of enhanced radar reflectivity when visualized on a plan position indicator display. An example of roost locations and daily dispersal of purple martins is depicted in Fig. 1. These data were collected using the WSR-88D (KINX) in Oklahoma. The most prominent "roost ring" is located about 40 km to the west of the radar, near Tulsa, Oklahoma. It has been estimated that this particular roost site attracts 100,000–250,000 purple martins annually. Flight patterns of the martins and other roosting species produce a distinct divergent flow field as seen in the Doppler velocity data shown in the bottom panel of Fig. 1.

This example illustrates that an important biological application of NEXRAD is, perhaps ironically, what it tells us about the ecology and behavior of animals on the ground. In circumstances where animals are concentrated or unevenly distributed in the landscape prior to initiating flight en mass, weather radars operating at low elevation angles can map these locations by capturing patterns aloft as animals enter the airspace (Diehl et al. 2003). Using radar for identifying spatial distributions and use of terrestrial habitats of volant animals promises to inform conservation and management of such species as bats, migratory birds, and emergent insects. Radar observations have further potential for assessing the use of aerial habitats and quantifying how animals use both aerial and terrestrial landscapes. Research advances in radar technology and data mining to quantify how flying animals use both terrestrial and aerial habitats will be informative for both basic and applied ecological research (Kunz and Horn 2008; Buler and Diehl 2009).

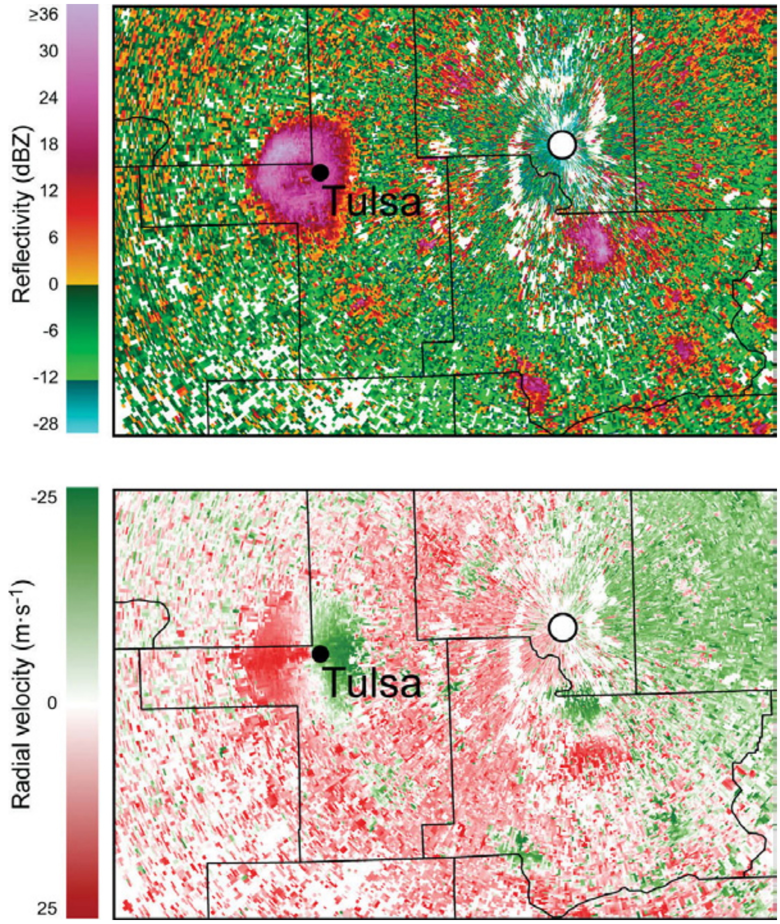


Fig. 1. (top) Reflectivity and (bottom) Doppler velocity data collected on 2 Aug 2009 using the WSR-88D (KINX) located near Tulsa, OK. The location of KINX is indicated by the white circle. The departure of purple martins from a roosting site resulted in the ring-shaped region of echo located just west of Tulsa. The Doppler velocity data indicate radial motion outward from the roost at the center of the ring.

Because many species of flying animals perform ecological services that aid human society (e.g., Abramovitz 1998; Cleveland et al. 2006; Losey and Vaughan 2006; Sekercioglu 2006; Bayon and Jenkins 2010; Kunz et al. 2011), there are considerable economic consequences related to our ability to enumerate how these animals use both the airscape and the landscape. Radar has been used to detect the movements of agricultural pest species directly (Leskinen et al. 2011) as well as capture their spatial encounters with foraging bats (Westbrook 2008). Indeed, the potential to quantify aerial densities of bats using radar may directly inform on the efficacy of bats as natural biological predators of agricultural pest insects. For instance, the economic benefits of Brazilian free-tailed bats (*Tadarida brasiliensis*) to cotton growers in the Winter Garden area of Texas was estimated at roughly 15% of the total cotton harvest (Cleveland et al. 2006). Radar-based monitoring of waterfowl populations may guide management decision in relation to hunting regulations and is already being explored as a method of quantifying the effects of waterfowl habitat restoration (J. Buler 2011, personal communication). Although there will always be a need for on-the-ground monitoring in species management and conservation, radar shows promise as an effective remote sensing tool for identifying daily and migratory behavioral patterns. Efforts to use radar in lieu of other more labor intensive monitoring techniques may help relieve pressure on strained state and federal natural resource budgets.

RADAR AEROECOLOGY AND SCALE ANALYSIS. The concept of aeroecology promotes a broad and integrative approach when investigating the aerosphere and the myriad airborne organisms it supports. The same applies to radar aeroecology, which not only encompasses observations of bioscatter using radio waves but also focuses on the spatial and temporal activity of organisms that broadly correlate with meteorological events over a wide range of temporal and spatial extents. Movements of organisms in the aerosphere are also likely influenced by innate biological factors as well as a variety of meteorological conditions, including wind (Walls et al. 2005; Liechti 2006) and weather fronts (Shamoun-Baranes et al. 2010). The extent to which meteorological factors influence volant animals (the degree of causality) can also be related to scale, as shown in Fig. 2. Although studies have examined the role of scale on causal relationships between weather and climate and biological systems (e.g., Clark 1985; Alerstam 1996; Berthold 1998; Peterson et al. 1998; Shamoun-Baranes et al. 2010), additional work is needed and would be facilitated within the framework of radar aeroecology.

It is common practice in meteorology to categorize certain phenomena according to discrete spatial scales, such as microscale (0–2 km), mesoscale (2–2,000 km), and macroscale (2,000 km and larger) (Orlanski 1975). These categories can be further subdivided into even smaller domains related not only to meteorological but also to biological phenomena (Westbrook and Isard 1999), including predator–prey interactions and other types of foraging behaviors with different dimensions depending upon the species of interest (Fig. 2). For example, a single bat may forage over many kilometers on a given night while hunting for aerial insects, but a single predatory event may last only a second. Macroscale meteorological events, such as storms, likely influence seasonal and daily movements of both prey and predators that use the aerosphere, whereas microscale meteorological events, such as turbulent eddies in the planetary boundary layer, could influence the frequency and successes of local predatory behavior. At intermediate and larger scales, many species engage in nomadic wandering and daily and nightly dispersal behaviors. Because of the challenges associated with following the movements of individuals (particularly volant animals), daily, nightly, and seasonal dispersal events are among the least well-studied life history phases of many species (Andreassen et al. 2002).

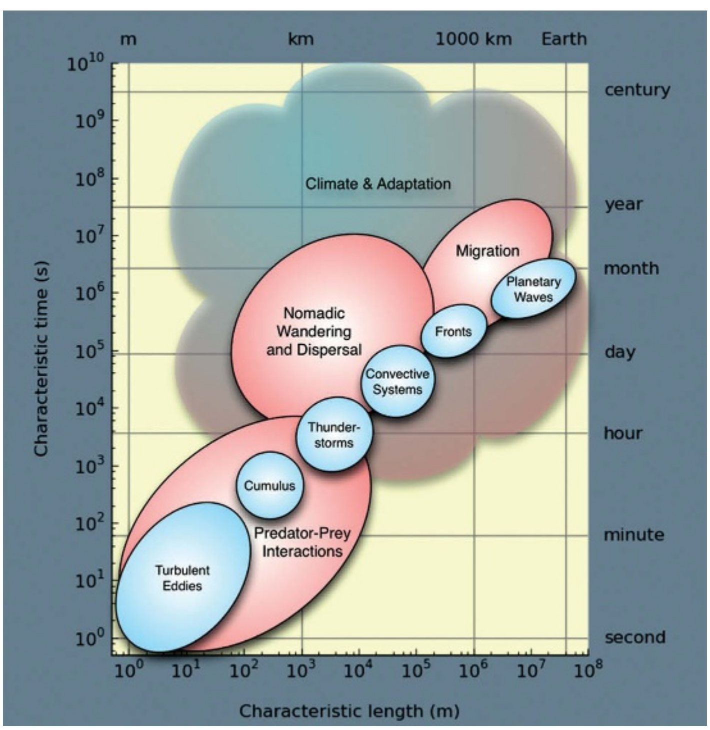


Fig. 2. Depiction of the spatial and temporal scales of common meteorological phenomena and movement patterns of organisms supported by the aerosphere, which can be observed by radar. Regions of overlap indicate those scales at which movements of airborne organisms could be influenced by prevailing meteorological conditions.

Annual migratory behaviors involve seasonal movements from warm subtropical or temperate regions to cool temperate regions in the spring to avoid limited food resources, followed by the return migration in the fall to avoid mortality due to cold temperature and a lack of food resources (Alerstam 1990; Fleming and Eby 2003; Newton 2008; Cryan and Diehl 2009; Bowlin et al. 2010; Faaborg et al. 2010; Robinson et al. 2010). Seasonal migration to avoid reduced food resources in winter is emblematic of the connectedness among meteorological and ecological phenomena at seasonal temporal and spatial scales. Migratory animals are also influenced by daily meteorological conditions. The effects of the spatial and temporal variability of daily, weekly, and monthly weather on migration demonstrate the multiscale complexity of the connections between weather, climate, and migratory behavior of volant animals (Richardson 1978; Sparks et al. 2002).

Adaptation, geography, and climate underlie evolutionary, ecological, and meteorological phenomena to the extent that meteorological conditions influence heritable aspects of survival and reproduction (fitness) of individuals. Although conceptually the multiscale linkages among climate, weather, and animal movement behaviors are easy to grasp (Clark 1985), there has been a limited ability to empirically test hypotheses about the influence of daily and seasonal meteorological conditions on animal movements in the aerosphere due to the technological and logistical challenges of collecting data at the appropriate spatial and temporal scales (Bowlin et al. 2010). The use of national and international networks of radars and a radar aeroecology program promises to obtain greater understanding of movements and behaviors of volant organisms using radar observations over different spatial and temporal scales coupled with ancillary data, such as meteorological conditions and local biological sampling.

VALIDATION OF RADAR SIGNAL ORIGINS. Understanding the behavior of volant animals at local scales is key to understanding their broad patterns of movement in the aerosphere. The effective use of radar as a means of monitoring such movements requires fundamental knowledge of how radio waves interact with bioscatterers. That is, one must carefully explore the theoretical and experimental assumptions applied to radar observations in the process of weather forecasting and the extraction of bioscatter. Before one can effectively study bioscatter over large domains and consider how it is revealed through NEXRAD, careful investigations are needed to determine how bioscatterers are revealed using single-radar platforms and over small spatial domains. Detailed studies at small spatial scales will also lead to better classification of bioscatter and estimates of numerical densities, which then can be used in basic ecological research (e.g., mosaic bioscatter maps), conservation planning (e.g., stopover habitat assessments), and assessing anthropogenic mortality factors (e.g., collisions of birds with aircraft and interactions of birds and bats with wind turbines and other tall structures).

As discussed in Bruderer (2003) and Larkin (2005), radar systems for biological research can be grouped into broad categories based on beam geometry. Fan-beam radars include airport surveillance radars, air traffic control radars, and ship navigation or marine radars. The formed beam pattern generally spans about 2° or less horizontally and 10°–35° vertically. Such radars are relatively inexpensive and therefore often used in the field to observe bioscatterers. The radar is placed on a trailer or truck with the antenna and is allowed to rotate about a vertical axis at a fixed elevation angle. Although the broad vertical beam is unsatisfactory for obtaining information on height, some radar systems can be configured such that the antenna can be rotated about a horizontal axis as well, providing height data (Mabee et al. 2006)

In contrast to wide fan-beam systems, pencil-beam radars include weather radars, tracking radars, and wind profilers. These systems project a narrow conical beam. Antennas for pencil-beam radars are typically mounted on a pedestal that allows the radar antenna to be fixed in position or scan in azimuth and elevation. Fixed-beam radars, for example, may point vertically to observe bioscatterers as they pass overhead through the sampling volume.

Single-radar installations offer a quantitative means of regularly observing the many types of periodic movements of volant animals in the vicinity of the radar, such as insect eruptions (Reynolds et al. 2008), nightly foraging activity of bats emerging from roosts (Kunz and Horn 2008), premigration staging of purple martins (Russell and Gauthreaux 1999), and winter roosts of tree swallows (Winkler 2006). Routine monitoring of daily and seasonal movement patterns permits robust testing of hypotheses about potential deviations from natural variability due to perturbations from climatic variability, natural disasters, land use, urbanization, and other anthropogenic factors.

A major challenge in using radar as a biological research tool is determining the origin of received signals. Radar signals can result from backscatter caused by precipitation, various forms of aerosols, turbulence-induced gradients in the refractive index, biological organisms, buildings, trees, and so forth (Larkin 2005). They can also be produced by radio wave interference from a host of terrestrial to intergalactic sources. Discriminating bioscatter from other sources of radar signals as well as among biological taxa is crucial for maximizing the utility of radar for biological research. Some methods for signal discrimination include using the temporal and spatial characteristics of the region associated with the received radar signal (Lakshmanan et al. 2010), a signal's velocity and polarimetric attributes when available (Bachmann and Zrnić 2007), and in the case of bioscatter, the wing-beat characteristics of the flying birds, bats, and insects (Zaugg et al. 2008), and the natural history of their movements (Diehl and Larkin 2005; O'Neal et al. 2012).

Researchers have used several methods of "ground truth" to identify animals observed on radar, including observing birds migrating at night by watching the disc of the moon (Lowery and Newman 1955), passive thermal imaging (Gauthreaux and Livingston 2006), night vision equipment (Mabee et al. 2006), acoustic monitoring of calls made in flight (Larkin et al. 2002; Farnsworth et al. 2004), and combinations of such methods (Liechti et al. 1995). Additional methods of identifying bioscatter in radar data have been proposed (Gauthreaux and Belser 1998; Zrnić and Ryzhkov 1998; Bachmann and Zrnić 2007; Schmaljohann et al. 2008; Mead et al. 2010). Here, we only consider two of these radar techniques: wing-beat frequency and radar polarimetry.

The rate at which a particular volant animal flaps its wings is determined by a variety of parameters related to characteristics of the air through which it is flying and the animal itself (e.g., Pennycuick 2001; Bullen and McKenzie 2002; Hedenström 2008). Among those pertaining to the animal are body size, body mass, wing span, wing area, and so forth. As birds, bats, and insects engage in flight, changes in their body shape resulting from wing beating produce corresponding changes in the amount of their body surfaces exposed to probing radio waves. These changes appear on radar as periodic fluctuations in backscattered radio wave signals (Bruderer et al. 2010). Radar-measured wing-beat patterns differ considerably between major taxonomic groups of flying animals, particularly between insects and vertebrates, such as birds and bats. Algorithms operating on these data can discriminate between wing-beat patterns and classify individual bioscatterers into broad taxonomic categories (Vaughn 1985; Zaugg et al. 2008).

In Fig. 3 we present an example of how wing-beat patterns in radar data differ between flying animals that vary considerably in size and shape. Shown are time series of received signals corresponding to three different flying animals taken with an X-band radar during a study of fall-migrating ducks in Illinois (O'Neal et al. 2010). The wing beats of the insect shown in the top time series are rapid and shallow, presumably related to its mass and flight kinematics. Songbirds can interrupt flapping with occasional coasting (middle time series), flap continuously, or rapidly alternate between flapping and coasting. The bottom time series shows the wing-beat pattern of a single dabbling duck, probably a mallard (*Anas platyrhynchos*). The time series of traces from flying birds show considerable detail in beat-to-beat consistency and such fine structure is commonly observed with radar, but this fine structure does not persist when birds are illuminated from different orientations.

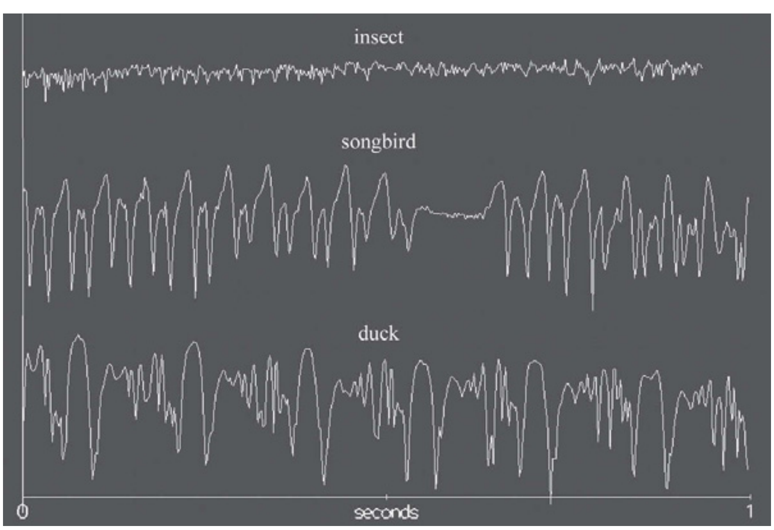


Fig. 3. Wing beats of single animals on an X-band radar. The time series of received power (arbitrary scale) over a 1-s interval are sampled at the 2087 s^{-1} pulse rate of the radar as the animals fly through the narrow, stationary beam of the radar. The data were collected as "radar ground truth" in a study of fall-migrating ducks on WSR-88D, coming off wetland areas in Illinois (O'Neal et al. 2010).

Radar polarimetry techniques provide another means of discriminating between different observed species. For a dual-polarization radar, horizontally and vertically polarized radio waves are transmitted and received either simultaneously or alternatingly (Doviak et al. 2000). The amount of received backscattered power for the two different polarizations not only depends on the size and composition of a scatterer but also on its shape and orientation. A large raindrop having an oblate spheroidal shape will produce more backscatter in the horizontal polarization than in the vertical polarization. The differential reflectivity (Z_{DR}), which is the ratio of radar reflectivity (Z) computed from the horizontal and vertical polarizations, is used as a measure of aspect from radar scatter. Some of the earliest uses of Z_{DR} for the study of airborne fauna involved explorations into the role of insects as the source of "clear air" echoes in weather radar (Mueller and Larkin 1985; Achtemeier 1991). Additional dual-polarimetric parameters, which we will not discuss here, have also been used for discriminating biological scatter from atmospheric scatter (Zrnić and Ryzhkov 1998; Bachmann and Zrnić 2007; Melnikov et al. 2011; Moisseev et al. 2010).

We recently completed a series of radar observations using the National Oceanic and Atmospheric Administration (NOAA) mobile X-band (3-cm wavelength) dual-polarized weather radar (NO-XP) to observe Brazilian free-tailed bats in Texas during the summer of 2010. Using the NO-XP, which has a beam width of approximately 1°, we were able to make detailed observations of multiple colonies of bats as they emerged from their roosts and departed on nightly foraging bouts. Figure 4 shows data collected when the radar was positioned about 11 km south of the location of Frio Cave, near Uvalde, Texas. This and other caves in south-central Texas are known to host large maternity colonies of Brazilian free-tailed bats that aggregate during the spring and summer to give birth and to raise young (Kunz and Robson 1995). The NO-XP measurements shown in Fig. 4 correspond to an elevation angle of 3°, and the NEXRAD data represent composite values from the National Severe Storms Laboratory (NSSL)'s mosaic radar product the National Mosaic and Multi-Sensor Quantitative Precipitation Estimation (NMQ) system (see below).

Dual-polarization products, such as Z_{DR}, can be used to discriminate between insects and bats because they are sensitive to the shape of the scattering target. For the most part, large (≈5 dB) values of Z_{DR} shown in the figure correspond to insects. After the bats dispersed and began feeding on insects, they exhibit strongly negative Z_{DR} values (around −6 dB; not shown). The cause for these values has been the subject of investigation and could be related to resonant scatter (Zrnić and Ryzhkov 1998). The availability of such dual-polarization parameters will make it possible to better understand the foraging behaviors of bats in response to the location and distribution of insects.

The NEXRAD network in the United States is currently undergoing a dual-polarimetric upgrade (Doviak et al. 2000), which should be completed by 2013. Dual-polarimetric radars provide a powerful means of discriminating between biological and nonbiological scatter and among different biological taxa. Similar to hydrometeor classifications based on dual-polarization characteristics that are currently in use (Straka et al. 2000), several biological

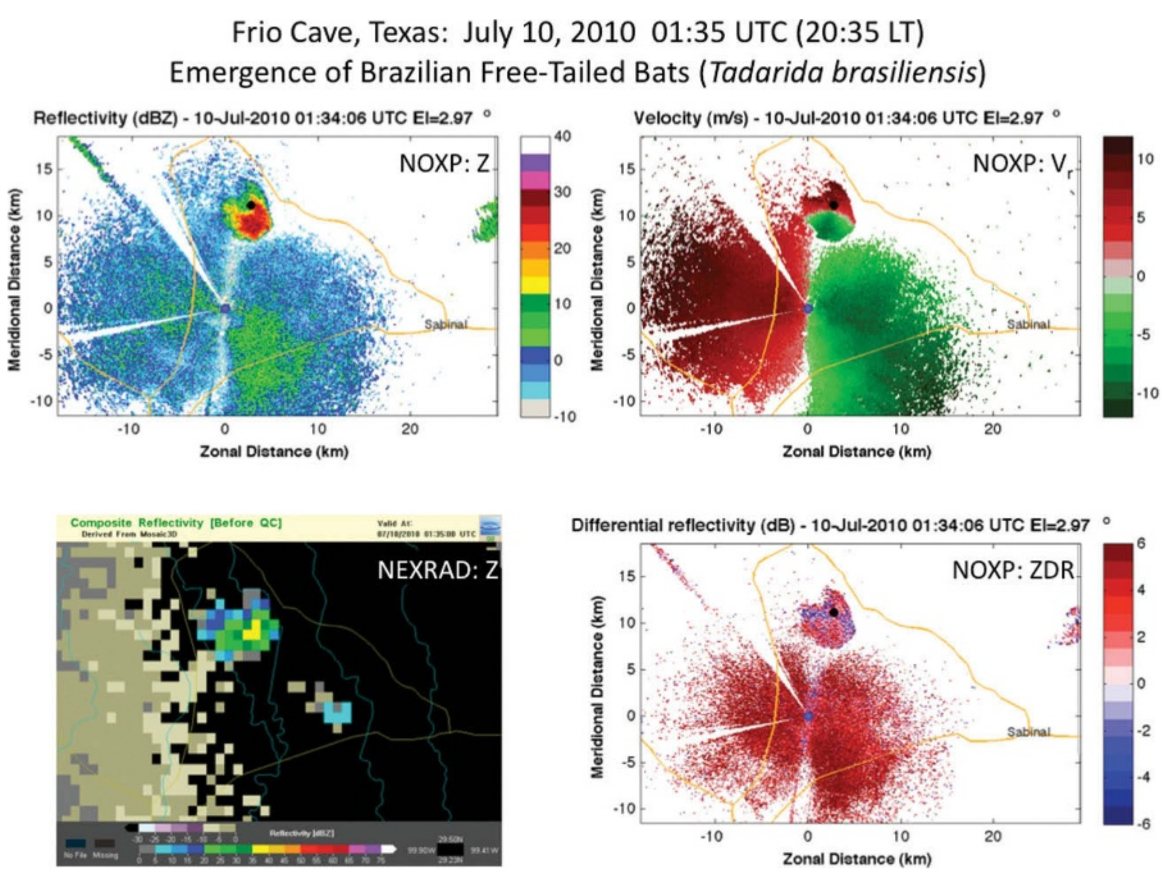


Fig. 4. Radar data showing emergence of Brazilian free-tailed bats from Frio Cave collected using NEXRAD and NO-XP. Shown are values for *Z*, radial velocity (V_r), and Z_{DR}. The black dot denotes the location of Frio Cave from which the bats are emerging. The bulk of the scatter is from insects. The NO-XP data were collected using an elevation angle of 3°, and the NEXRAD reflectivity data are composite values.

classification algorithms are being developed (Moisseev et al. 2010). Access to data from these radars at S band (frequency used by NEXRAD), C band (frequency used at many airports), and X band (frequency used for smaller radar networks and many mobile radars) for overlapping spatial and temporal domains promises to provide signal-processing tools for a wide range of novel meteorological and biological applications.

ANIMAL DENSITIES FROM RADAR DATA.

Some biological questions can be explored simply by observing changes in the spatiotemporal patterns present in bioscatter data, whereas other investigations require a more quantitative form of analysis. There are numerous examples in the literature demonstrating how radar can be used to record backscatter from individuals, or groups of birds, bats, and insects in flight (Liechti et al. 1995; Gauthreaux and Belser 1998; Gauthreaux et al. 2008; Schmaljohann et al. 2008; Dokter et al. 2010). Ground truth and validation data collected using modeling exercises or through radar experiments conducted in the laboratory or in the field are necessary to empirically resolve scaling issues that impact the translation of radar data into biologically meaningful units, such as the number densities of organisms, which can be used for basic ecological research and conservation planning. Such estimates will contain both process and sampling errors, resulting in varying levels of uncertainty, and thus validation studies are needed to determine the extent of these uncertainties and to assess the accuracy and utility of these methods.

The smallest spatial grain of biological scatter that can be observed by radar corresponds to the physical dimensions of the organism itself. Under the right conditions, the intensity of bioscatter can be related to the number density of the airborne individuals sampled by the radar. For such an analysis, the scattering properties of the animal (e.g., size, shape, aspect, and composition) must be known. These properties can be observed in the laboratory under controlled conditions and applied to bioscatter data in the field or measured directly in the field (Edwards and Houghton 1959; Vaughn 1985).

Using the laboratory facilities at the University of Oklahoma, some of us have recently made radar cross section (RCS) measurements of a live Brazilian free-tailed bat at X band (Fig. 5). The bat was tethered using nylon line that allowed motion of its wings and simulated flight while its body was held stationary inside an anechoic chamber. A 12-in. metal sphere was used to calibrate the equipment. Using these data, the backscattered power corresponding to the sphere and the bat were calculated. From such RCS measurements, it is possible to convert measured values of radar reflectivity into counts or number densities of bats observed at the same radar wavelength.

If the observing radar has been properly calibrated, then the retrieved RCS can be used to estimate the individual body size of a given organism (Riley 1985; Wolf et al. 1993). Backscatter from animals whose size is similar to that of the wavelength falls into the complicated Mie (resonant) region, so that greater RCS values do not necessarily relate linearly to larger body sizes (Vaughn 1985). Additionally, animals have irregular shapes that may further complicate such measurements. As an approximation of the RCS of a particular bioscatterer (i.e., animal), an alternate approach is to consider a spherical volume of water of the same mass (Eastwood 1967; Vaughn 1985; Martin and Shapiro 2007).

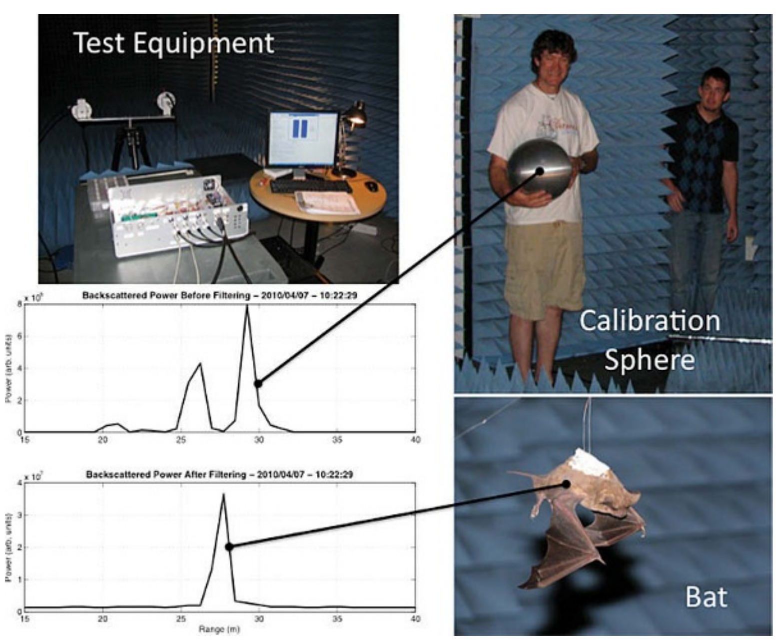


Fig. 5. RCS measurements made in the anechoic chamber of the University of Oklahoma's Radar Innovations Laboratory. Data of a live tethered bat were collected using a low-powered X-band pulsed Doppler radar. A 12-in. metal sphere was used for calibration. Results are shown in the plots. Similar data are being collected for other species.

As an alternative to laboratory or theoretical calculations, one can also estimate the RCS value for a particular species with a well-calibrated radar in conjunction with visual surveys (Larkin 1991; Schmaljohann et al. 2008; O'Neal et al. 2010). This is typically performed using a pencil-beam radar to estimate numbers and visual surveys to verify the species being observed. Two radars can be used when quantifying numbers or number densities of bioscatterers, such that a smaller, mobile radar is used for validation at small scales and a larger, stationary radar (e.g., WSR-88D) is used for extended spatial coverage of bioscatter patterns (Diehl et al. 2003; Schmaljohann et al. 2008; Dokter et al. 2010; O'Neal et al. 2010).

The accuracy of quantitative predictions based on radar data will depend on the spatial distribution of the animals in the aerosphere. For example, the equivalent radar reflectivity (Z_e) reported for NEXRAD WSR-88D radars is calculated under the assumption that the power returned from any volume of the atmosphere results from a uniform distribution of scatterers within that volume. While this assumption may be well founded for broad front songbird migrations (Nebuloni et al. 2008), it is less clear how well it applies when scatterers fill only a portion of the radar beam or when the distribution of foragers or migrants is clumped. Although beam blockage or attenuation will almost always be negligible with biological backscatter, nonlinear additivity and the exact shape of the beam are nevertheless important to consider. Detailed studies at small spatial scales are needed, which can lead to better classification of bioscatter and accurate estimates of densities of airborne organisms.

USING NEXRAD TO MONITOR THE AEROSPHERE. In meteorology, multiple instrument platforms are incorporated to investigate the atmosphere. Similar approaches have also been adopted to learn about the dynamics of aerial organisms in large aggregations (e.g., Lowery and Newman 1955; Liechti et al. 1995; Larkin et al. 2002; Gauthreaux and Livingston 2006; Mabee et al. 2006). Small portable radars, adapted for biological research, are powerful tools for investigating the behavior of individual or small groups of animals in the aerosphere, but they typically have a limited sampling domain. Larger radar installations, such as the NEXRAD network, provide extended coverage but at the expense of spatial and temporal resolution. The spatial domain of behavioral processes of biological aggregations, such as bat and bird colonies, typically falls within the coverage of a single WSR-88D and can be used to investigate the nightly and daily emergence and foraging behavior of insectivorous bats (Kunz and Horn 2008).

Focusing our attention on the macroscale phenomena depicted in Fig. 2, it is clear that an integrative approach involving a network of radars is needed to optimally monitor and interpret bioscatter at regional to continental scales. The NEXRAD network consists of multiple WSR-88D installations, with 156 of these distributed across the United States. The extent of horizontal coverage provided by NEXRAD depends on altitude and the area of interest, but most of the eastern half of the continental United States can be observed at an altitude of 3 km (Maddox et al. 2002). Coverage at this altitude is considerably reduced along the Rocky Mountains and to the west (Maddox et al. 2002). This situation improves, however, if we are able to add other networked operational radars, such as terminal Doppler weather radars, airport surveillance radars, and air route surveillance radars (Weber et al. 2007). Furthermore, a network of small X-band radars could significantly improve coverage near the surface and in mountainous regions (McLaughlin et al. 2009).

A concerted effort has been made to make current and archived NEXRAD data available to the public via the Internet (Kelleher et al. 2007). Data from individual WSR-88D installations along with visualization software are free from the National Climatic Data Center. So-called level II radar products are available as reflectivity, radial velocity, and spectrum width presented in a spherical coordinate system centered at the radar site. In addition to the level II data, several derived and estimated level III meteorological products are also available as discussed below. In addition to meteorologists and atmospheric scientists, some biological research groups have begun incorporating NEXRAD data into their research programs (see, e.g., the provided references to the work done by Gauthreaux and colleagues); however, the task of integrating the data across radar sites can be challenging.

The NOAA NSSL, in collaboration with the Federal Aviation Administration (FAA), has instituted a highly effective means of fusing data from these radar systems along with observations from other instruments into one collective data product. Within the framework of the NMQ system, base level II NEXRAD data are ingested, controlled for quality, and combined to form a 3D reflectivity map projected onto a Cartesian grid (Zhang et al. 2004, 2011). The horizontal resolution of the NMQ output is 1 km with 31 vertical levels and a temporal resolution of 5 min. A weighting function is employed in those regions corresponding to overlapping radar coverage (Zhang et al. 2005).

The NMQ project provides a host of severe weather and QPE products, which are provided to governmental agencies and academic institutions in quasi real time. Many of these data products can be retrieved from a publicly accessible web portal (http://nmq.ou.edu/). Such a resource will be useful for researching bioscatter because biologists who are interested in the collective behavior of airborne organisms on a daily and seasonal basis and at multiple spatial scales can observe phenomena seldom detectable with other existing technologies. The recent observational and analytical capability of NMQ will stimulate new hypotheses about animal movements and interactions in the aerosphere and provide a framework for testing such hypotheses through data mining and quantitative analyses and visualizations of archived and real-time data (e.g., Kelly et al 2012).

A display from the NMQ web portal corresponding to composite reflectivity at 0300 UTC 17 May 2010 is depicted in Fig. 6. The top image shows the merged reflectivity data before applying algorithms for quality control (QC), which attempt to remove nonmeteorological effects (Lakshmanan et al. 2010). We refer to these as non-QC data. In addition to the weather signal, these non-QC reflectivity values contain contributions from bioscatterers, sun spikes, anomalous propagation, and radio interference. Bioscatter corresponding to the northward nocturnal spring migration of birds in the eastern United States, along with echoes from bats emerging from large cave roosts, comprise the dominant contribution to signals. Because most birds and all bats migrate at night, radar provides an excellent tool for monitoring mass migratory movements. The bottom image has been subjected to the NMQ quality control as discussed in Zhang et al. (2011) and references therein. Both the quality-controlled and non-QC data are currently available from the NMQ web portal, with the latter serving as a base reference when examining weather outputs.

Having access to gridded fields of reflectivity data produced through

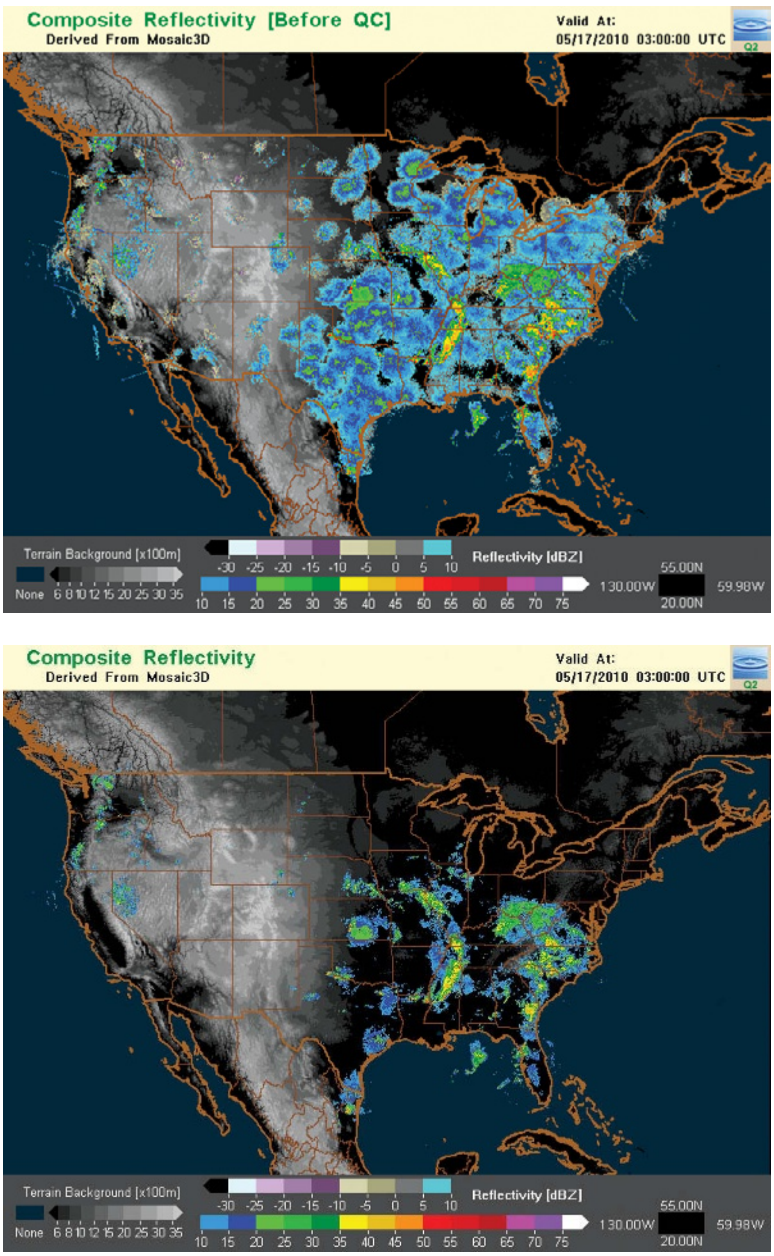


Fig. 6. Displays of composite reflectivity obtained from the NMQ web portal at 0300 UTC 17 May 2010. (top) Reflectivity maps before applying QC to remove nonmeteorological effects. The date is near the peak of the nocturnal spring migration of songbirds in the northern part of the United States; insects and probably bats also contribute to the radar return. (bottom) The same data after QC. The underlaid gray shading denotes the terrain elevation with lighter colors representing higher elevations.

NMQ not only enables the study of macroscale biological processes involving organisms that use the aerosphere but also facilitates a comparison with other continental-scale datasets, such as those containing meteorological quantities. Consider, for example, the radar data from NMQ shown in Fig. 7, corresponding to the emergence and subsequent dispersal of Brazilian free-tailed bats from their day roosts in south-central Texas during July 2010. Often the bats initially disperse in all directions, resulting in a signature ring shape (Fig. 7), which is similar to that associated with the departure of the purple martins (Fig. 1). The reflectivity and velocity data shown in Fig. 1 correspond to a single WSR-88D site (KINX), but the results shown in Fig. 6 have been merged from several WSR-88D sites. Four of these WSR-88D sites—KSJT, KGRK, KDFX, and KEWX—are depicted in Fig. 7. Also shown are the locations of four roost sites—Rucker Cave, Frio Cave, Ney Cave, and Bracken Cave. Regions of enhanced reflectivity in the vicinity of the roost sites resulting from the emerging bats are clearly evident. After emerging from their roosts, birds and bats may orient in one or more preferred directions based on the prevailing meteorological conditions and the availability of food resources. In the case of emerging bats shown in Fig. 7, the location and abundance of the food source (insects) is likewise affected by both current and seasonal weather conditions.

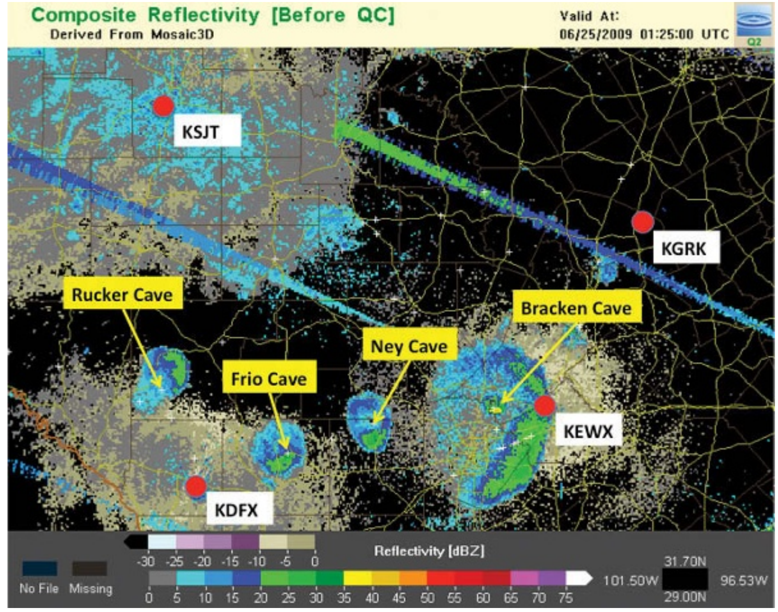


Fig. 7. An example of roost rings resulting from the emergence of Brazilian free-tailed bats in south-central Texas as observed in the non-QC composite reflectivity data produced through NMQ. The image corresponds to observations made at 0125 UTC (2025 CDT) 25 Jun 2009 as the bats were dispersing from their roosts at dusk to feed on insects. Since these data were collected at dusk, sun spurs can also be seen in the images. Also shown are the locations of WSR-88D sites and bat roosts.

When investigated over the span of several years, NMQ data can be used to look for shifts in patterns of emergence. Further, the NMQ data can be used to test hypotheses about causes of these shifts, and whether group behavior at bat or bird colonies can be observed and explained in terms of both biotic and nonbiotic influences. For instance, in Fig. 8 we show time series of NMQ output calculated over a 24-h period corresponding to the locations of the roost sites depicted in Fig. 7. Data streams of radar data, surface observations, satellite measurements, and other parameters can be visualized directly using the NMQ website (top panel) or downloaded and then processed and displayed using a variety of software packages (bottom panel). The values shown in the top panel of Fig. 8 were computed using data corresponding to the NMQ grid cell (1-km^2 grain size) nearest to the cave location. For the time series plotted in the bottom panel, the maximum value of Z over a 3×3 grid on NMQ cells surrounding the cave locations were used.

The evening emergences of bats can be seen in the reflectivity data for each of the sites as peaks occurring at dusk between 0000 and 0200 UTC [1900–2100 central daylight time (CDT)]. This is followed by elevated values of reflectivity until they return from foraging at sunrise. Enhancements in the reflectivity between 1200 and 1400 UTC (0700–0900 CDT) indicate the return of the bats. In the case of Bracken Cave, a double fly-out pattern can be seen in the time series data of Z: one occurs just after 0000 UTC and other at around 0125 UTC (corresponding to Fig. 7). The roost ring from the initial emergence as well as the beginning of the second can be seen in Fig. 7 as the bats return from their first nightly feeding bout (Kunz et al. 1995).

NATIONAL BIOSCATTER DATABASE. Any investigation of the effects of changes in land cover and climate on ecological patterns and processes requires a sufficient time series at a continental scale. Few time series datasets have been collected in a consistent and uniform manner that can be used to scale from a grain size of 1 km to a continental domain. Networks of radar installations, such as NEXRAD, could be used to provide the information needed to test hypotheses regarding the timing, distribution, and abundance of active migration and foraging events in unprecedented ways. However, monitoring and interpreting the time series of bioscatter at a continental scale that lends itself to aeroecological studies will require a workflow that not only integrates the national network of radars into a uniform dataset but also one that has biological significance, including ground truth verification of the identity of volant animals. The next step in promoting the utility of radar aeroecological research is to develop and create derived products analogous to those available within the level III NEXRAD data but with a diverse user community in mind; that is, we need level III products geared for uses beyond atmospheric science per se.

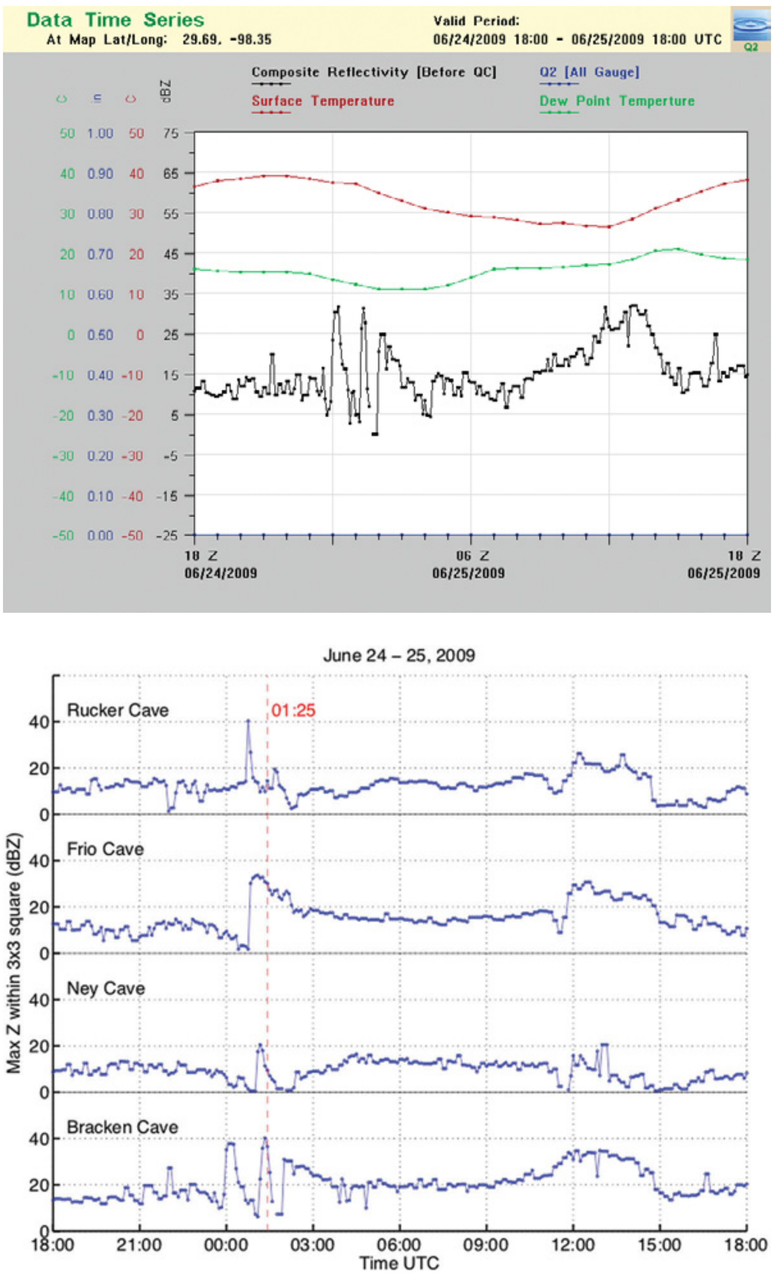


Fig. 8. Time-series data from NMQ corresponding to the four different bat roosts depicted in Fig. 7. (top) Data streams for Bracken Cave representing different observed quantities: reflectivity, rainfall rate (Q2), surface temperature, and surface dewpoint temperature. Here, Q2 refers to data from tipping-bucket rain gauges. (bottom) Time series of reflectivity values for all four cave locations. Both plots span the same 24-h period. The vertical red dashed line in the bottom plot marks the time depicted in Fig. 7.

In Fig. 9 we present an illustration of how NEXRAD data could be used to create level III products tailored to both meteorologists and ecologists and to potential cross-disciplinary research outputs. The NEXRAD level III meteorological data products are already heavily used by many government agencies and private sector enterprises. We expect that the proposed NEXRAD level III biological products will also have a significant impact if they are made readily available for the entire continental United States. They will not only foster many areas of biological research but also promote crossover studies between meteorology and biology as illustrated in Fig. 9. This type of crossover research between biology and meteorology is expected to benefit investigations into the potential impacts of climatic variability.

Radar biological data will continue to be gathered within constraints imposed by meteorological conditions. Therefore, before attempting to create a database of level III biological products, we should carefully consider the nature of the data that actually go into constructing the NMQ national mosaic. Depending on meteorological conditions, each of the WSR-88Ds is operated in one of several scanning modes or volume coverage patterns (VCPs), which set the radar's rotation rate, sampling period, number of elevation angles, and so forth. Each VCP has been designed to meet certain agency specifications. For example, the reported average return power and radial velocity should be accurate to within 1 dB and 1 m s^{-1}, respectively. Since the VCPs have been optimized for meteorological—rather than biological—conditions, the sensitivity of the radar to bioscatter will vary depending on the type of VCP being used. That is, a radar operating in a VCP mode designed for observations of clear air would be more appropriate for observations of migrating songbirds than the same radar running a VCP designed for observations of precipitation.

Moreover, one must factor in the separation between a particular region of bioscatter and the next nearest WSR-88D, as the distance between bioscatterers and radar installation will affect the lowest altitude that can be sampled. This accounts for the disk-shaped patches of enhanced reflectivity depicted in the top panel of Fig. 6 are centered on individual radar sites. The combined effects of the Earth's curvature and the fact that the lowest elevation angle sampled by NEXRAD is seldom less than 0.5° means that airborne fauna located at moderate heights can only be detected if they occur in airspace near a radar site. Fortunately, the effects of geometry (location of the radar sites with respect to the biological scatterers) and scanning parameters (the type of VCP being used) are known and can be considered when interpreting data (Buler and Diehl 2009).

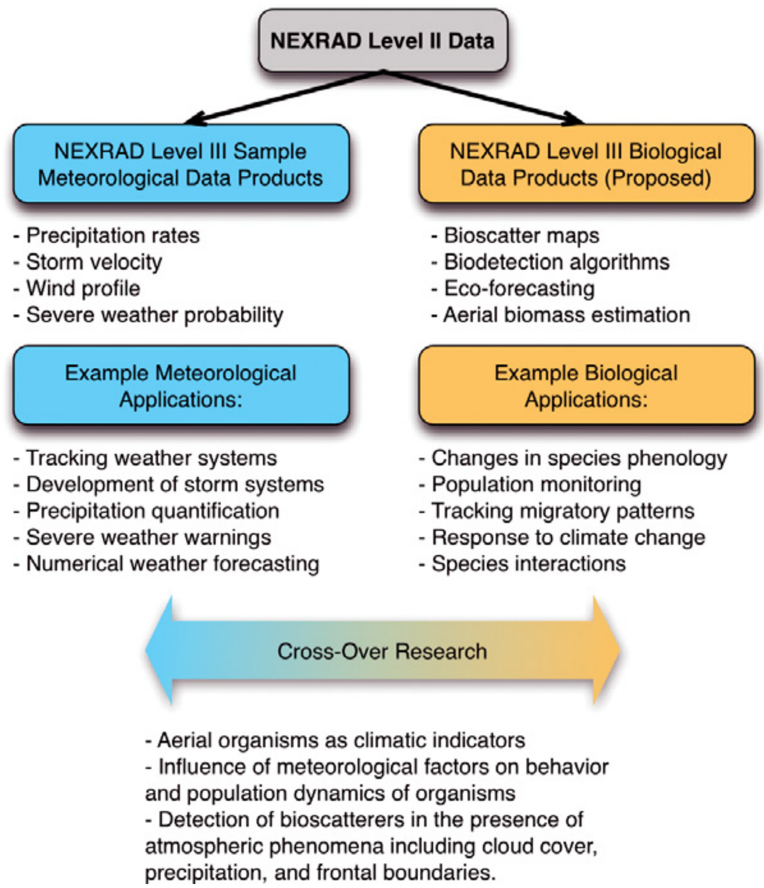


Fig. 9. Illustration showing some of the conventional meteorological products generated using NEXRAD data and some proposed biological counterparts. The proposed level III biological products when taken together with the existing meteorological products are expected to promote new crossover areas of research.

Bearing in mind that caution should be exercised when interpreting radar data in terms of bioscatter, we feel that level III biological products should be created for both archived and real-time data. Maps depicting these products will be particularly powerful when coupled with climate, land cover, and phenological data that match both the temporal and spatial scales of the radar archive. For example, most volant animals are too small to carry energy reserves for more than a few days; thus, they often respond rapidly to their local environment (Bowlin et al. 2010; Robinson et al. 2010; Bridge et al 2011). By comparing changes in land cover and climate with the timing and rate of changes in foraging, migratory, and stopover behaviors, we can test hypotheses about the magnitude of these local effects on animal behaviors and the spatiotemporal scaling of different species. Improving our ability to track aerial movements of birds, bats, and arthropods, however, remains a primary challenge in biology (Wilcove and Wikelski 2008; Holland and Wikelski 2009; Bowlin et al. 2010).

Recent advances in Doppler radar technology and networking can be correlated with detailed data on individual behaviors to work toward a mechanistic understanding of animal responses to land cover and climate. Tracking methods, such as radio transmitters, geolocators, and tracking radar, provide valuable data on individual animal movements usually at local to regional spatial scales. Generally, individual tracking methods are limited to short time spans (days, weeks, or at most a year). In contrast, the NEXRAD archive provides a near-continuous time series of the distribution and abundance of all airborne animals over the continental United States (Bowlin et al. 2010; Robinson et al. 2010; Bridge et al 2011). Data from tracking individual animals could be coupled with a nearly 20-yr radar archive (1993–2012) of continental-scale animal movement data to take advantage of the strengths of both approaches. Whereas information on movements from individual animals could help us interpret radar observations, the NEXRAD data archive promises to provide critical insights into how the aerosphere–lithosphere dynamic is being impacted by local, regional, and continental patterns of changes in climate and land cover.

SUMMARY AND CONCLUSIONS. Airborne animals are highly responsive to environmental change in the terrestrial landscape (Herkert 1994; Murphy 2003) and aerosphere (Shamoun-Baranes et al. 2010), and depend heavily on the interface between the Earth's surface and the aerosphere. In particular, migrating fauna must respond rapidly to their environment to find adequate refuge and acquire sufficient energy to endure diverse conditions they will likely encounter en route during migration. These animal movements represent convergent and sometimes coevolved phenotypic traits shaped by natural selection to take advantage of predictable shifts in seasonal patterns (phenology) of ecosystem productivity (Pulido 2007; Kunz and Horn 2008; Hedenström 2008). Some of the most compelling evidence of biological responses to changes in climate and land cover comes from experiments and observations of migratory and aerial foraging behaviors at local scales compared with the availability of food and climatic variability (Wilkinson and Fleming 1996; Buskirk et al. 2009; Bridge et al. 2010). Understanding individual behavioral responses to environmental changes is fundamental to a mechanistic understanding of aeroecological dynamics and will build a foundation for predicting consequences of future environmental change. The emerging discipline of aeroecology seeks to understand these important ecological mechanisms and the role of meteorological variability on aeroecological dynamics.

Since its inception, radar has proven to be a valuable tool for studying animals in the aerosphere. Numerous technological developments have had a significant impact on the field of radar aeroecology during the ensuing years. One of these has been the use of radar polarimetry, a technique used to better discriminate bioscatter from weather signals and to better distinguish between birds, bats, and insects (Mueller and Larkin 1985; Zrnić and Ryzhkov 1998). Advancements in radar polarimetry for biological studies may have a significant impact on aeroecological research in light of the planned upgrade of NEXRAD to include such capabilities (Doviak et al. 2000). Moreover, continued advancements in computer and networking technology are making it progressively easier to process large volumes of data and to make them readily available to a wide community of users. The time has come for meteorologists, radar scientists, biologists, and others to work more closely together on developing radar products that will contribute to a better understanding of airborne fauna. These could be similar, for example, to the current level III data and distributed frequently on a Cartesian coordinate system (as is done through the NMQ project). Such a database could be easily queried, mined, and related to other databases containing meteorological and geographic information system content to provide a powerful research tool for answering important transdisciplinary questions. Although much of this paper focused on radar aeroecology within the United States using operational networks and NEXRAD in particular, much of the discussion applies to single-radar installations or other radar networks. The application of radars for biological research should also be considered as integral to new radar systems, such as networked X-band radars (McLaughlin et al. 2009) and phased array weather radars (Zrnić et al. 2007).

ACKNOWLEDGMENTS. We are grateful to Kara Bolognini, Paul A. Heady III, Fanxing Kong, Benjamin J. O'Neal, Danny Scipíon, and Ryan Shipley for their valuable assistance during the collection and processing of data presented in this paper. We also appreciate the value inputs provided by three anonymous reviewers. PBC was funded in part through the National Oceanic and Atmospheric Administration National Severe Storms Laboratory Grant NA08OAR4320904. THK received support from the National Science Foundation (Grant EIA-0326483) and the Air Force Office of Scientific Research (Grants FA9550-09-1-0415, FA9550-10-1-0442). WFF was supported by the National Science Foundation through Grant DBI- 0905881. JFK was supported by National Science Foundation Grants IOS-0541740 and EPS- 0919466. Steve Parker provided access to his property for operation of the NO-XP near Frio Cave. Bain Walker provided access to the Frio Cave property.

REFERENCES

Abramovitz, J. N., 1998: Putting a value on nature's "free" services. *World Watch,* **11,** 10–19.

Achtemeier, G. L., 1991: The use of insects as tracers for "clear-air" boundary-layer studies by Doppler radar. *J. Atmos. Oceanic Technol.,* **8,** 746–765.

Alerstam, T., 1990: *Bird Migration*. Cambridge University Press, 420 pp.

——, 1996: The geographical scale factor in orientation of migrating birds. *J. Exp. Biol.,* **199,** 9–19.

Andreassen, H. P., N. C. Stenseth, and R. A. Ims, 2002: Dispersal behaviour and population dynamics of vertebrates. *Dispersal Ecology,* J. M. Bullock, R. E. Kendward, and R. S. Hails, Eds., Blackwell Sciences Ltd., 237–256.

Bachmann, S., and D. S. Zrnić, 2007: Spectral density of polarimetric variables separating biological scatterers in the VAD display. *J. Atmos. Oceanic Technol.,* **24,** 1186–1198.

Bayon, R., and M. Jenkins, 2010: The business of biodiversity. *Nature,* **466,** 184–185.

Berthold, P., 1998: Spatiotemporal aspects of avian long-distance migration. *Spatial Representation in Animals,* S. Healy, Ed., Oxford University Press, 103–118.

Bonter, D. N., S. A. Gauthreaux Jr., and T. M. Donovan, 2009: Characteristics of important stopover locations for migrating birds: Remote sensing with radar in the Great Lakes basin. *Conserv. Biol.,* **23,** 440–448.

Bowlin, M. S., and Coauthors, 2010: Grand challenges in migration biology. *Integr. Comp. Biol.,* **50,** 261–279.

Bridge, E. S., J. F. Kelly, P. E. Bjornen, C. M. Curry, P. H. C. Crawford, and J. M. Paritte, 2010: Effects of nutritional condition on spring migration: Do migrants use resource availability to keep pace with a changing world. *J. Exp. Biol.,* **213,** 2424–2429.

Bruderer, B., 1997a: The study of bird migration by radar. Part 1: The technical basis. *Naturwissenschaften,* **84,** 1–8.

——, 1997b: The study of bird migration by radar. Part 2: Major achievements. *Naturwissenschaften,* **84,** 45–54.

——, 2003: The radar window to bird migration. *Avian Migration,* P. Berthold, E. Gewinner, and E. Sonnenschein, Eds., Springer Verlag, 347–358.

——, D. Peter, A. Boldt, and F. Liechti, 2010: Wing-beat characteristics of birds recorded with tracking radar and cine camera. *Ibis,* **152,** 272–291.

Buderi, R., 1998: *The Invention that Changed the World: The Story of Radar from War to Peace*. Abacus, 575 pp.

Buler, J. J., and R. H. Diehl, 2009: Quantifying bird density during migratory stopover using weather surveillance radar. *IEEE Trans. Geosci. Remote Sens.,* **47,** 2741–2751.

Bullen, R. D., and N. L. McKenzie, 2002: Scaling bat wingbeat frequency and amplitude. *J. Exp. Biol.,* **205,** 2615–2626.

Buskirk, J. V., R. S. Mulvihill, and R. C. Leberman, 2009: Variable shifts in spring and autumn migration phenology in North American songbirds associated with climate change. *Global Change Biol.,* **15,** 760–771.

Chapman, J. W., V. A. Drake, and D. R. Reynolds, 2011: Recent insights from radar studies of insect flight. *Annu. Rev. Entomol.,* **56,** 337–356.

Clark, W. C., 1985: Scales of climate impacts. *Climatic Change,* **7,** 5–27.

Cleveland, C. J., and Coauthors, 2006: Economic value of the pest control service provided by Brazilian free-tailed bats in south-central Texas. *Front. Ecol. Environ.,* **4,** 238–243.

Cryan, P. M., and R. H. Diehl, 2009: Analyzing bat migration. *Ecological and Behavioral Methods for the Study of Bats,* T. H. Kunz and S. Parsons, Eds., John Hopkins University Press, 476–488.

Diehl, R. H., and R. P. Larkin, 2005: Introduction to the WSR-88D (NEXRAD) for ornithological research. *Bird Conservation Implementation and Integration in the Americas: Proceedings of the Third International Partners in Flight Conference,* C. J. Ralph and T. D. Terrell, Eds., Vol. 2, USDA Forest Service General Tech. Rep. PSW-GTR-191, 876–888.

——, ——, and J. E. Black, 2003: Radar observations of bird migration over the Great Lakes. *Auk,* **120,** 278–290.

Dokter, A. M., F. Liechti, H. Stark, L. Delobbe, P. Tabary, and I. Holleman, 2010: Bird migration flight altitudes studied by a network of operational weather radars. *J. Roy. Soc. Interface,* **8,** 30–43, doi:10.1098/rsif.2010.0116.

Doviak, R. J., and D. S. Zrnić, 1993: *Doppler Radar and Weather Observations*. 2nd ed. Academic Press, 562 pp.

——, V. Bringi, A. Ryzhkov, A. Zahrai, and D. Zrnić, 2000: Considerations for polarimetric upgrades to operational WSR-88D radars. *J. Atmos. Oceanic Technol.,* **17,** 257–278.

Eastwood, E., 1967: *Radar Ornithology*. Methuen & Co. Ltd., 278 pp.

Edwards, J., and E. W. Houghton, 1959: Radar echoing area polar diagram of birds. *Nature,* **184,** 1059.

Faaborg, J., and Coauthors, 2010: Recent advances in understanding migration systems of New World land birds. *Ecol. Monogr.,* **80,** 3–48.

Farnsworth, A., S. A. Gauthreaux Jr., and D. van Blaricom, 2004: A comparison of nocturnal call counts of migrating birds and reflectivity measurements on Doppler radar. *J. Avian Biol.,* **35,** 365–369.

Fleming, T. H., and P. Eby, 2003: Ecology of bat migration. *Bat Ecology,* T. H. Kunz and M. B. Fenton, Eds., University of Chicago Press, 156–208.
Gauthreaux, S. A., Jr., 2006: Bird migration: Methodologies and major research trajectories (1945–1995). *Condor,* **98,** 442–453.
——, and C. G. Belser, 1998: Displays of bird movements on the WSR-88D: Patterns and quantification. *Wea. Forecasting,* **13,** 453–464.
——, and ——, 2003: Bird movements on Doppler weather surveillance radar. *Birding,* **35,** 616–628.
——, and J. W. Livingston, 2006: Monitoring bird migration with a fixed-beam radar and a thermal imaging camera. *J. Field Ornithol.,* **77,** 319–328.
——, ——, and C. G. Belser, 2008: Detection and discrimination of fauna in the aerosphere using Doppler weather surveillance radar. *Integr. Comp. Biol.,* **48,** 12–23.
Hedenström, A., 2008: Adaptations to migration in birds: Behavioural strategies, morphology and scaling effects. *Philos. Trans. Roy. Soc. London,* **B363,** 287–299.
Herkert, J. R., 1994: The effects of habitat fragmentation on midwestern grassland communities. *Ecol. Appl.,* **4,** 461–471.
Holland, R. A., and M. Wikelski, 2009: Studying the migratory behavior of individual bats: Current techniques and future directions. *J. Mammal.,* **90,** 1324–1329.
Kelleher, K. E., and Coauthors, 2007: Project CRAFT: A real-time delivery system for NEXRAD level II data via the Internet. *Bull. Amer. Meteor. Soc.,* **88,** 1045–1057.
Kelly, J. F., J. R. Shipley, P. B. Chilson, K. W. Howard, W. F. Frick, and T. H. Kunz. 2012. Quantifying animal phenology in the aerosphere at a continental scale using NEXRAD weather radars. *Ecosphere,* **3,** 16. doi:10.1890/ES11-00257.1
Kunz, T. H., and S. K. Robson, 1995: Postnatal growth and development in the Mexican free-tailed bat, *Tadarida brasiliensis*: Size at birth, age estimation, and growth rates. *J. Mammal.,* **76,** 769–783.
——, and J. W. Horn, 2008: Analyzing NEXRAD Doppler radar images to assess nightly dispersal patterns and population trends in Brazilian free-tailed bats (*Tadarida brasiliensis*). *Integr. Comp. Biol*., **48,** 24–39.
——, J. O. Whitaker Jr., and M. D. Wadanoli, 1995: Dietary energetics of the Mexican free-tailed bat (*Tadarida brasiliensis*) during pregnancy and lactation. *Oecologia*, **101,** 407–415.
——, and Coauthors, 2008: Aeroecology: Probing and modeling the aerosphere. *Integr. Comp. Biol*., **48,** 1–11.
——, E. B. de Torrez, D. M. Bauer, T. Lobova, and T. H. Fleming, 2011: Ecosystem services provided by bats. *Ann. N. Y. Acad. Sci.,* **1223,** 1–38.
Lack, D., and G. C. Varley, 1945: Detection of birds by radar. *Nature*, **156,** 446.
Lakshmanan, V., J. Zhang, and K. Howard, 2010: A technique to censor biological echoes in radar reflectivity data. *J. Appl. Meteor. Climatol.,* **49,** 435–462.
Larkin, R. P., 1991: Flight speeds observed with radar, a correction: Slow "birds" are insects. *Behav. Ecol. Sociobiol.,* **29,** 221–224.
——, 2005: Radar techniques for wildlife. *Techniques for Wildlife Investigation and Management,* C. E. Braun, Ed., Wildlife Society, 448–464.
——, W. R. Evans, and R. H. Diehl, 2002: Nocturnal flight calls of dickcissels and Doppler radar echoes over south Texas in spring. *J. Field Ornithol.,* **73,** 2–8.
Leshem, Y., and Y. Yom-Tov, 1996: The magnitude and timing of migration by soaring raptors, pelicans and storks over Israel. *Ibis,* **138,** 188–203.
——, and ——, 1998: Routes of migrating soaring birds. *Ibis,* **140,** 41–52.
Leskinen, M., and Coauthors, 2011: Pest insect immigration warning by an atmospheric dispersion model, weather radars and traps. *J. Appl. Entomol.,* **135,** 55–67.
Liechti, F., 2006: Birds: Blowin' by the wind? *J. Ornithol.,* **147,** 202–211.
——, B. Bruderer, and H. Paproth, 1995: Quantification of nocturnal bird migration by moonwatching: Comparison with radar and infrared observations. *J. Field Ornithol.,* **66,** 457–652.
Losey, J. E., and M. Vaughan, 2006: The economic value of ecological services provided by insects. *Bioscience,* **56,** 311–323.
Lowery, G. H., and R. J. Newman, 1955: Direct studies of nocturnal bird migration. *Recent Studies in Avian Biology,* A. Wolfson, Ed., University of Illinois Press, 238–263.
Mabee, T. J., B. A. Cooper, J. H. Plissner, and D. P. Young, 2006: Nocturnal bird migration over an Appalachian ridge at a proposed wind power project. *Wildl. Soc. Bull.,* **34,** 682–690.
Maddox, R. A., J. Zhang, J. J. Gourley, and K. W. Howard, 2002: Weather radar coverage over the contiguous United States. *Wea. Forecasting,* **17,** 927–934.
Martin, W. J., and A. Shapiro, 2007: Discrimination of bird and insect radar echoes in clear air using high-resolution radars. *J. Atmos. Oceanic Technol.,* **24,** 1215–1230.
McLaughlin, D., and Coauthors, 2009: Short-wavelength technology and the potential for distributed networks

of small radar systems. *Bull. Amer. Meteor. Soc.,* **90,** 1797–1817.

Mead, R., J. Paxton, and R. S. Sojda, 2010: New software methods in radar ornithology using WSR-88D weather data and potential application to monitoring effects of climate change on bird migration. *Proc. iEMSs 2010: Int. Congress on Environmental Modelling and Software,* Ottawa, ON, Canada, IEMSs, W.01.04.

Melnikov, V., M. Leskinen, and J. Koistinen, 2010: Spectral polarimetric parameters of radar signals from atmospheric biota. [Available online at www.erad2010.org/pdf/POSTER/Wednesday/04_Others/09_ERAD2010_0208_extended_modificat.pdf.]

Moisseev, D., M. Leskinen, and T. Aittomäki, 2010: Radar signal quality improvements by spectral processing of dual-polarization radar measurements. *Proc. Sixth European Conf. on Radar in Meteorology and Hydrology,* Sibiu, Romania, National Meteorological Administration, 1–8. [Available online at www.erad2010.org/pdf/oral/wednesday/advances2/1_ERAD2010_0246.pdf.]

Mueller, E. A., and R. P. Larkin, 1985: Insects observed using dual-polarization radar. *J. Atmos. Oceanic Technol.,* **2,** 49–54.

Murphy, M. T., 2003: Avian population trends within the evolving agricultural landscape of eastern and central United States. *Auk,* **120,** 20–34.

Nebuloni, R., C. Capsoni, and V. Vigorita, 2008: Quantifying bird migration by a high-resolution weather radar. *IEEE Trans. Geosci. Remote Sens.,* **46,** 1867–1875.

Newton, I., 2008: *The Migration Ecology of Birds*. Academic Press, 984 pp.

O'Neal, B. J., J. D. Stafford, and R. P. Larkin, 2010: Waterfowl on weather radar: Applying ground-truth to classify and quantify bird movements. *J. Field Ornithol.,* **81,** 71–82.

——, ——, and ——, 2011: Stopover duration of fall-migrating dabbling ducks. *J. Wildl. Manage.,* **76,** 285–293..

Orlanski, I., 1975: A rationale subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.,* **56**, 527–530.

Pennycuick, C. J., 2001: Speeds and wingbeat frequencies of migrating birds compared with calculated benchmarks. *J. Exp. Biol.,* **204,** 3283–3294.

Peterson, G., C. R. Allen, and C. S. Holling, 1998: Ecological resilience, biodiversity, and scale. *Ecosystems,* **1,** 6–18.

Pulido, F., 2007: The genetics and evolution of avian migration. *Bioscience,* **57**, 165–174.

Reynolds, D. R., 1988: Twenty years of radar entomology. *Antenna,* **12,** 44–49.

——, A. D. Smith, and J. W. Chapman, 2008: A radar study of emigratory flight and layer formation by insects at dawn over southern Britain. *Bull. Entomol. Res.,* **98,** 35–52.

Richardson, W. J., 1978: Timing and amount of bird migration in relation to weather: A review. *Oikos,* **30,** 224–272.

Riley, J. R., 1985: Radar cross sections of insects. *Proc. IEEE,* **73,** 228–232.

Robinson, W. D., and Coauthors, 2010: Integrating concepts and technologies to advance the study of bird migration. *Front. Ecol. Environ.,* **8,** 354–361.

Russell, K. R., and S. A. Gauthreaux Jr., 1999: Spatial and temporal dynamics of a purple martin roost premigratory roost. *Wilson Bull.,* **111,** 354–362.

——, D. S. Mizrahi, and S. A. Gauthreaux Jr., 1998: Large-scale mapping of purple martin pre-migratory roosts using WSR-88D weather surveillance radar. *J. Field Ornithol.,* **69,** 316–325.

Schmaljohann, H., F. Liechti, E. Bächler, T. Steuri, and B. Bruderer, 2008: Quantification of bird migration by radar – A detection probability problem. *Ibis,* **150,** 342–355.

Sekercioglu, C. H., 2006: Increasing awareness of avian ecological function. *Trends Ecol. Evol.,* **21,** 464–471.

Serafin, R. J., and J. W. Wilson, 2000: Operational weather radar in the United States: Progress and opportunity. *Bull. Amer. Meteor. Soc.,* **81,** 501–518.

Shamoun-Baranes, J., and Coauthors, 2008: Avian information systems: Developing web-based bird avoidance models. *Ecol. Soc.,* **13.** [Available online at www.ecologyandsociety.org/vol13/iss2/art38/.]

——, W. Bouten, and E. E. van Loon, 2010: Integrating meteorology into research on migration. *Integr. Comp. Biol.,* **50,** 280–292.

Sparks, T., H. Crick, N. Elkins, R. Moss, S. Moss, and K. Mylne, 2002: Birds, weather and climate. *Weather,* **57,** 399–410.

Straka, J. M., D. S. Zrnić, and A. V. Ryzhkov, 2000: Bulk hydrometeor calibration and quantification using polarimetric radar data: Synthesis of relations. *J. Appl. Meteor.,* **39,** 1341–1372.

van Belle, J., J. Shamoun-Baranes, E. van Loon, and W. Bouten, 2007: An operational model predicting autumn bird migration intensities for flight safety. *J. Appl. Ecol.,* **44,** 864–874.

Vaughn, C. R., 1985: Birds and insects as radar targets: A review. *Proc. IEEE,* **73,** 205–227.

Walls, S. S., R. E. Kenward, and G. J. Holloway, 2005: Weather to disperse? Evidence that climatic conditions influence vertebrate dispersal. *J. Anim. Ecol.,* **74,** 190–197.

Weber, M. E., J. Y. N. Cho, J. S. Herd, J. M. Flavin, W. E. Benner, and G. S. Torok, 2007: Next-generation multimission U.S. surveillance radar network. *Bull. Amer. Meteor. Soc.,* **88,** 1739–1751.

Westbrook, J. K., 2008: Noctuid migration in Texas within the nocturnal aeroecological boundary layer. *Integr. Comp. Biol.,* **48,** 99–106.

——, and S. A. Isard, 1999: Atmospheric scales of biotic dispersal. *Agric. For. Meteor.,* **97,** 263–274.

Wilcove, D. S., and M. Wikelski, 2008: Going, going, gone: Is animal migration disappearing? *Plos Biol.,* **6,** 1361–1364.

Wilkinson, G. S., and T. H. Fleming, 1996: Migration and evolution of lesser long-nosed bats *Leptonycteris curasoae*, inferred from mitochondrial DNA. *Mol. Ecol.,* **5,** 329–339.

Winkler, D. W., 2006: Roosts and migrations of swallows. *Hornero,* **21,** 85–97.

Wolf, W. W., C. R. Vaughn, R. Harris, and G. M. Loper, 1993: Insect radar cross-sections for aerial density measurements and target classification. *Trans. ASABE,* **36,** 949–954.

Zaugg, S., G. Saporta, E. van Loon, H. Schmaljohann, and F. Liechti, 2008: Automatic identification of bird targets with radar via patterns produced by wing flapping. *J. Roy. Soc. Interface,* **5,** 1041–1053.

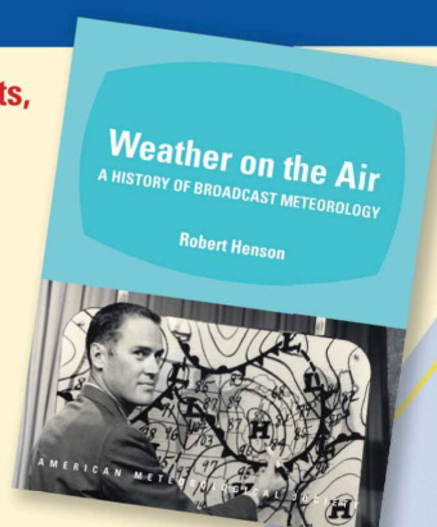
Zhang, J., K. Howard, C. Langston, S. Wang, and Y. Qin, 2004: Three- and four-dimensional high-resolution national radar mosaic. *Proc. Third European Conf. on Radar in Meteorology and Hydrology/COST 717 Final Seminar,* Visby, Sweden, 105–108.

——, ——, and J. J. Gourley, 2005: Constructing three-dimensional multiple radar reflectivity mosaics: Examples of convective storms and stratiform rain echoes. *J. Atmos. Oceanic Technol.,* **22,** 30–42.

——, and Coauthors, 2011: National Mosaic and Multi-Sensor QPE (NMQ) system: Description, results, and future plans. *Bull. Amer. Meteor. Soc.,* **92,** 1321–1338.

Zrnić, D. S., and A. V. Ryzhkov, 1998: Observations of insects and birds with polarimetric radar. *IEEE Trans. Geosci. Remote Sens.,* **36,** 661–668.

——, and Coauthors, 2007: Agile-beam phased array radar for weather observations. *Bull. Amer. Meteor. Soc.,* **88,** 1753–1766.



METEOROLOGICAL EDUCATION AND TRAINING USING A-TRAIN PROFILERS

BY THOMAS F. LEE, RICHARD L. BANKERT, AND CRISTIAN MITRESCU

Profiles from *CloudSat* and *CALIPSO*, atmospheric profilers within the NASA A-Train constellation, offer detailed observations of clouds, providing understanding that neither satellite imagers nor traditional sounders can convey.

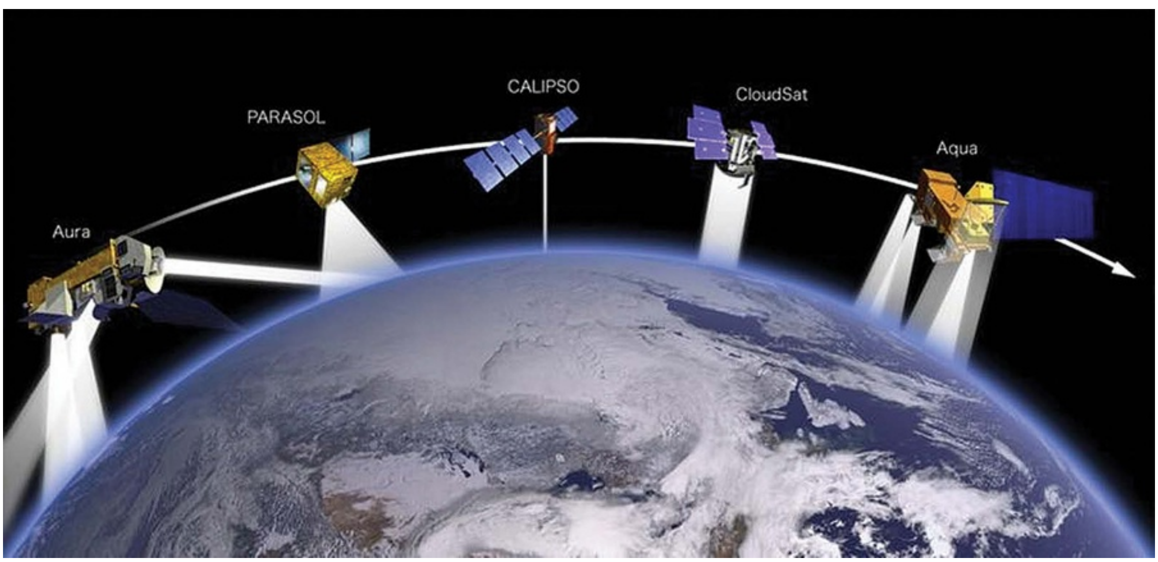


FIG. 1. A-Train constellation. Credit: NASA.

The potential for training forecasters and educating students is immense using data from the National Aeronautic and Space Administration's (NASA's) two A-Train (L'Ecuyer and Jiang 2010) profilers, *CloudSat* (Stephens et al. 2002) and *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (*CALIPSO*). In particular, the vertical profiles can provide crucial insights into two-dimensional features observed on satellite images and other traditional meteorological products. Launched on 28 April 2006, *CloudSat* is the first capability of its kind, a NASA Earth observation satellite that uses radar to infer vertical profiles of cloud properties. *CloudSat* flies in formation in the A-Train with several other satellites [*Aqua*, *Aura*, *CALIPSO*, and the French *Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar* (*PARASOL*)] whose orbits occur in the same path, one behind the other (Fig. 1). The examples of Posselt et al. (2008) suggest how effective use of *CloudSat* data can validate traditional conceptual models of midlatitude weather systems. Limited training has appeared on ▶

the World Wide Web, from the Cooperative Program for Operational Meteorology, Education and Training (COMET) Tropical Meteorology Textbook (www.meted.ucar.edu/tropical/textbook_2nd_edition/) and the Virtual Institute for Satellite Integration Training (VISIT; http://rammb.cira.colostate.edu/training/visit/). There are also examples on the Colorado State University Atmospheric Science web site (http://cloudsat.atmos.colostate.edu/). This article juxtaposes *CloudSat* profiles with corresponding satellite images to illustrate the education and training potential in a variety of atmospheric environments. An additional example covers the use of a *CALIPSO* profile to observe stratus and stratocumulus tops over and off the West Coast of the United States.

CloudSat's main sensor is the Cloud Profiling Radar (CPR), a 94-GHz nadir-viewing instrument that measures the returned backscattered energy by clouds as a function of height along the orbital track (Stephens et al. 2002). The CPR has a 240-m vertical range resolution between the surface and 30 km. Because of surface contamination from ground clutter, the usefulness of cloud information is quite limited near the surface. *CloudSat* observations provide a single row of pixels along its flight path with footprint size of 1.4 km × 1.7 km.

CloudSat produces accurate, high-resolution cloud heights and cloud vertical profiles (Kim et al. 2011). Unfortunately, it is capable of quantitatively profiling lightly precipitating cloud systems only (Mitrescu et al. 2010). For higher precipitation rates, complications arising from increased extinction and multiple scatter factors make quantitative precipitation analysis almost impossible. Despite these limitations *CloudSat* profiles can show precipitation features such as melting layers (or "bright bands") (Matrosov 2010), deep convective towers, orographic cloud systems, and multiple cloud layers. The capability to distinguish between convective and stratiform precipitating systems also exists.

AFFILIATIONS: Lee and Bankert—Naval Research Laboratory, Monterey, California; Mitrescu—Science Systems and Applications, Inc., Hampton, Virginia
CORRESPONDING AUTHOR: Thomas F. Lee, 7 Grace Hopper Ave., Monterey, CA 93943
E-mail: thomas.lee@nrlmry.navy.mil

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-11-00120.1

In final form 27 October 2011

Until 17 April 2011, when *CloudSat* experienced major battery problems and data became unavailable, the Naval Research Laboratory (NRL) posted products in near-real time on its NexSat web portal (Miller et al. 2006). Our near-real-time processing scheme is described in detail in Mitrescu et al. (2008). Product latency of about 4 h severely limited many nowcasting applications; however, missions such as the reconnaissance of oceanic tropical cyclones still benefited in spite of the delay. Data from future missions, if delivered much more promptly, could enable these profiles to be integrated into the forecast process.

The A-Train constellation, a configuration of clustered satellites in an early afternoon orbit, has several other instruments that are potentially useful for user training and education (Fig. 1). The *Aqua* satellite has the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) instrument that provides two-dimensional images of precipitation rates. *CloudSat* profiles may be used for detailed examination of the clouds responsible for the precipitation observed in AMSR-E retrievals (discussed later in conjunction with Fig. 14). The Moderate Resolution Imaging Spectroradiometer (MODIS), also onboard *Aqua*, yields detailed high-resolution true color images. The *CALIPSO* (Winker et al. 2009) instrument is a cloud lidar that can give important information about cloud height, cloud phase, and aerosol characteristics. Its capacity to profile cirrus, aerosols, and marine stratocumulus is unprecedented (Winker et al. 2010). Although these various A-Train satellite instruments are orbiting on separate platforms, together they comprise a single "virtual satellite" capability for which observations nearly coincide in time and space.

Examples and discussions in this article demonstrate how three-dimensional understanding can be improved by using the near-simultaneous display of profiles with the contemporaneous geostationary satellite imagery. For imagery, the geostationary Geocolor product is mainly used. This product is a visible and longwave infrared (0.63 and 10.8 μm) composite available 24 hours a day (Miller et al. 2006). It provides a single-channel visible image during the daytime, against the NASA "blue marble" background, and single-channel infrared image at night, against a background of nighttime lights. On the *CloudSat* profiles, temperature contours from the Navy Operational Global Atmospheric Prediction System (NOGAPS) are overlain for additional context in the vertical. To arrive at valid times corresponding to A-Train profiles, the NOGAPS data were interpolated between very short-term forecast times. Additionally, terrain height contours allow observation of orographic influences on clouds. For descriptions of the accompanying weather situations, daily weather maps archived by NOAA were consulted (www.hpc.ncep.noaa.gov/dailywxmap/).

EXAMPLES FOR TRAINING AND EDUCATION. *Cloud heights in the low/midtroposphere.* Identification of "open" vs. "closed" cell convection is a familiar exercise for satellite meteorology students. Figure 2 (7 April 2010) is an illustration of how *CloudSat* can sample the cloud vertical structure in both regimes. Note that open cells appear as bright dots in the Geocolor image composed of visible data northwest of a frontal system moving into the Pacific Northwest. Far south of the frontal system closed cells produce a near overcast in the trade wind regime. The *CloudSat* profile reveals the height of the open cells at about 4 or 5 km. To the south, the closed cells have only a height of approximately 1 or 2 km. The height of the closed cells in this example approaches 1.2 km, the lower limit of cloud tops detectable by *CloudSat* (Mitrescu et al. 2010).

CloudSat crosses a very shallow frontal band separating the air masses, with cloud heights comparable to the closed cells to the south. Nearly all the sampled band lies under the freezing-level height (according to NOGAPS temperature contours), suggesting that resulting precipitation, if any, should be from "warm rain" processes. This shallow frontal band is compared to much deeper systems later in the article. While experienced image interpreters may infer the shallow nature of the front in this region based on the image alone, new forecasters and students would benefit from the *CloudSat* comparison.

Marine stratocumulus and continental stratus clouds are usually too low to be well observed with *CloudSat*. However, *CALIPSO* profile data offer a powerful alternative to observe these cloud tops in comparison with imager products. In Fig. 3 (30 December 2007) both cloud system types occur under the same A-Train overpass. Topographically constrained stratus appears over California's Central Valley with marine stratocumulus to the south. The continental stratus has tops at approximately 1.2 km above mean sea level (MSL) over most of the valley, sloping upward to approximately 1.5 km above the slopes at the southern side of the valley and to nearly 2 km over the mountains at the northern side. To the south, the marine stratocumulus clouds have lower tops, sloping from about 0.7 km to the north to 1.0 km to the south. The north-to-south increase in height shown in this region is representative of summary statistics for stratocumulus prepared from *CALIPSO* data (Winker et al. 2010). Such variations in marine stratocumulus are tied to the height of the marine boundary layer (e.g., Bretherton et al. 2004). The tops of the stratocumulus clouds as observed by *CALIPSO* are difficult to derive from other weather satellite data (Minnis et al. 1992).

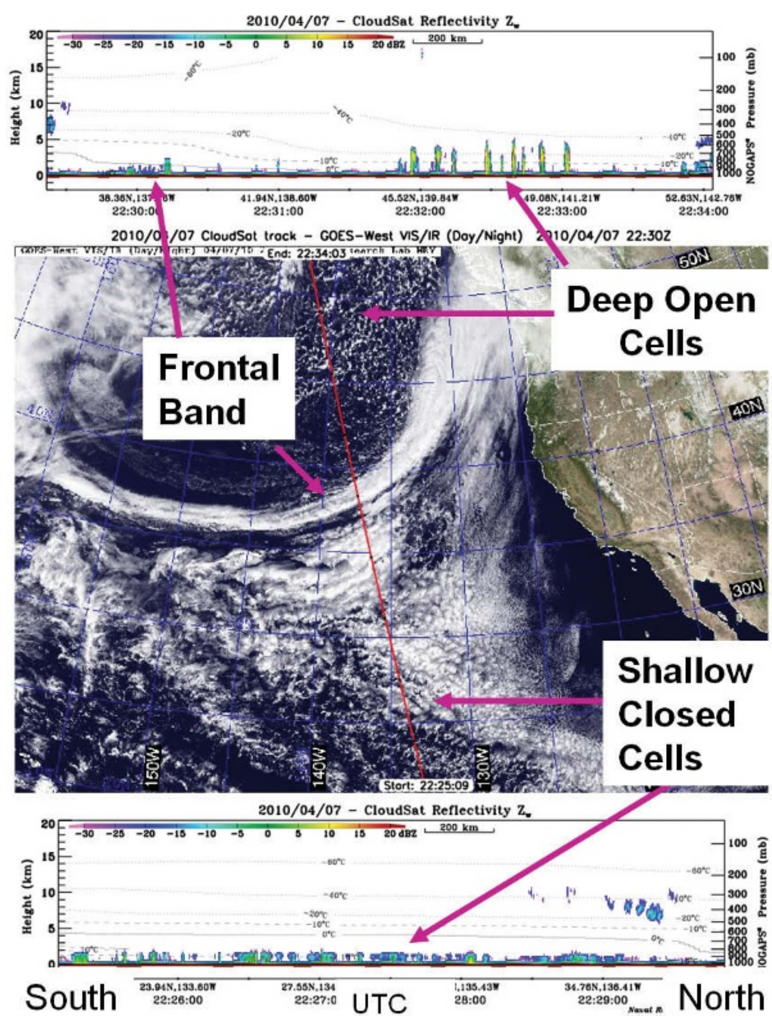


Fig. 2. (middle) Visible *GOES-11* Geocolor image, 2230 UTC 7 Apr 2010. Red line marks ascending *CloudSat* overpass path. (top) Northern and (bottom) southern portions of *CloudSat* radar reflectivity profile.

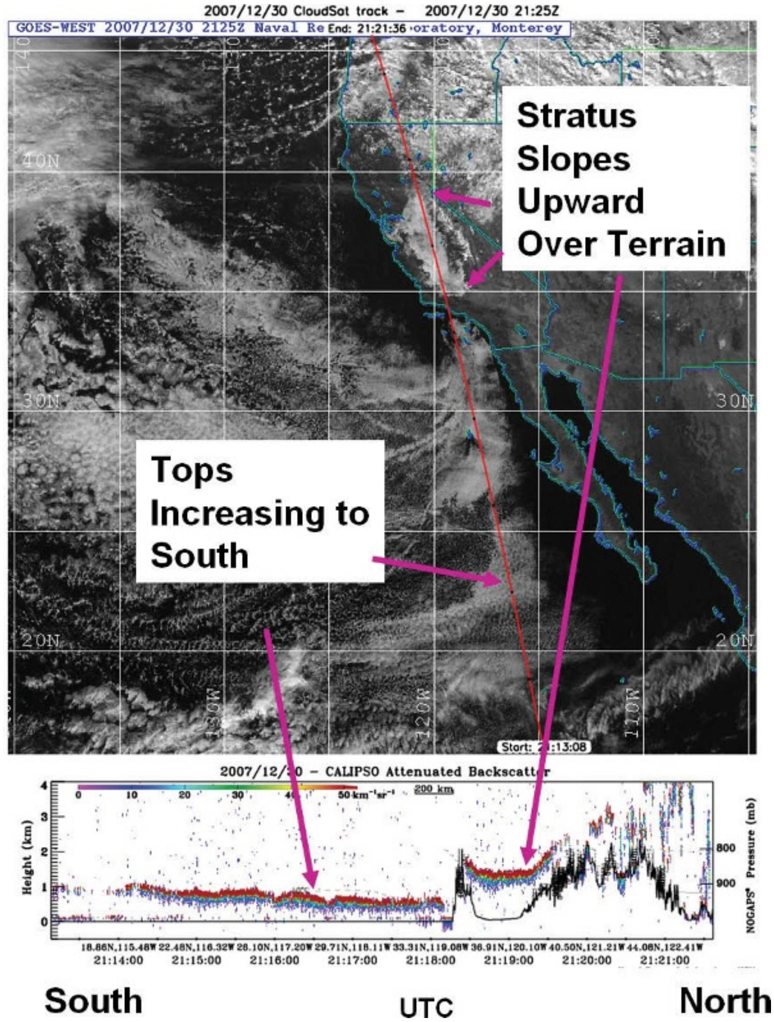


Fig. 3. (top) ***GOES-11*** **visible image, 2125 UTC 30 Dec 2007. Red line marks ascending** ***CALIPSO*** **overpass path. (bottom)** ***CALIPSO*** **attenuated backscatter profile.**

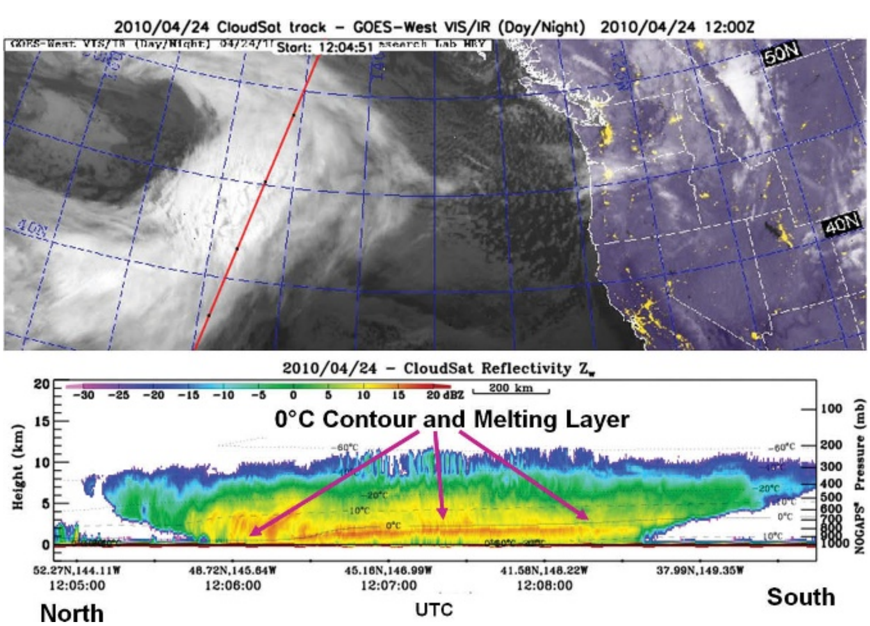


Fig. 4. (top) ***GOES-11*** **Infrared Geocolor image, 1207 UTC 24 Apr 2010. Red line marks descending** ***CloudSat*** **overpass path. (bottom)** ***CloudSat*** **radar reflectivity profile.**

Stability of frontal systems. Figures 4 (24 April 2010) and 5 (4 January 2008) demonstrate *CloudSat*'s ability to diagnose the stability of frontal systems. The Geocolor image in Fig. 4 [Geostationary Operational Environmental Satellite (GOES) infrared data] shows a frontal system in the North Pacific Ocean with *CloudSat* transecting the overrunning clouds in the warm sector. These clouds have a depth of approximately 10 km. Contrast this cloud depth with the much shallower frontal system from an earlier example (Fig. 2). Centered within the profile is an elongated bright band between about 1–2 km, representing the melting process. Bright bands are extremely common on *CloudSat* profiles within stratiform precipitation systems. As expected, the bright band lies just under the NOGAPS 0°C isotherm. This long and well-defined melting layer suggests a stable precipitation regime with steady warm sector precipitation. The bright band slopes downward at approximately 46°N (moving northward along the profile). The NOGAPS model also shows this decline in the 0°C level. Such changes in melting layer height are common in *CloudSat* reflectivity profiles, suggesting frontal discontinuities where the slope changes dramatically.

On 4 January 2008 a deep trough and associated polar air mass moved southeastward across the West Coast of the United States. The Geocolor image in Fig. 5 (top) depicts a *CloudSat* overpass through the associated cold frontal band. In contrast to the stable precipitation regime shown in Fig. 4, this *CloudSat* profile reveals embedded convection in the frontal band and the absence of an easily defined stable bright band. The Geocolor image confirms the unstable character of the precipitation with embedded convective cells off the northern California and Oregon coasts. Also of note is the orographic cloud tied to the Cascades on the *CloudSat* profile. This type of cloud is virtually impossible to detect on the nighttime longwave infrared image. Such orographic signatures are common in *CloudSat* data and will be discussed further in the next section.

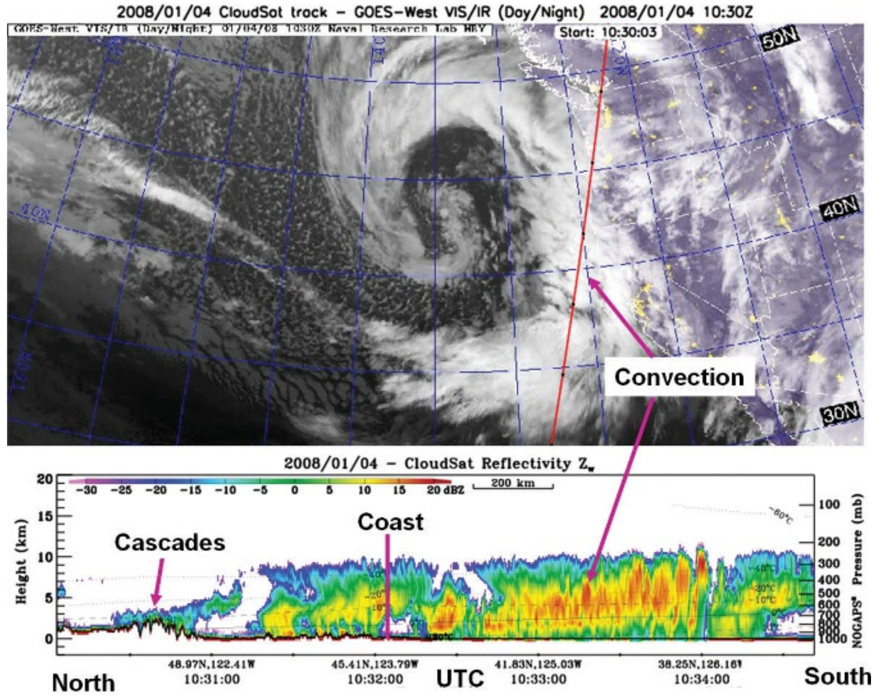


Fig. 5. (top) *GOES-11* Infrared Geocolor image, 1030 UTC 4 Jan 2008. Red line marks descending *CloudSat* overpass path. (bottom) *CloudSat* radar reflectivity profile.

Orographic influences on clouds. The strong effect of mountains on a coastal frontal system can be seen in Fig. 6 (3 December 2007). Precipitation from a cloud band apparent on the *GOES-11* longwave infrared image over Washington is corroborated by significant backscatter on the *CloudSat* profile. Significantly, precipitation and, to a large degree, clouds are absent from the lee of the Cascades, illustrating a strong rain shadow effect. Such comprehensive depictions of rain shadows are often not possible from ground-based weather radars because of the interference of terrain. The use of visible and, especially, longwave infrared satellite images is also limited due to the obscuration by higher clouds.

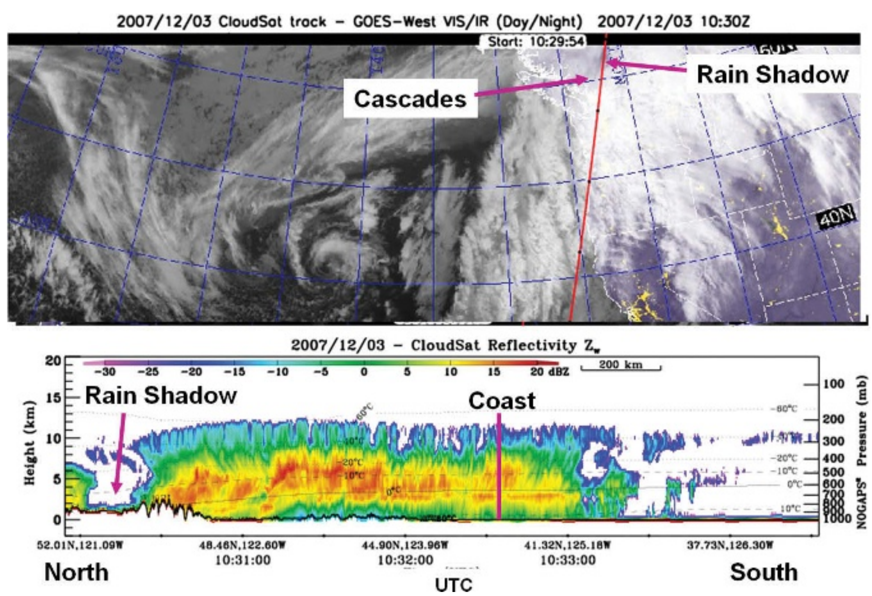


Fig. 6. (top) *GOES-11* Infrared Geocolor image, 1030 UTC 3 Dec 2007. Red line marks descending *CloudSat* overpass path. (bottom) *CloudSat* radar reflectivity profile.

Cloud layers. Cloud layering due to a split front (Browning and Monk 1982) is marked by an extensive region of saturated ascending air aloft, on the order of 100 km ahead of shallow clouds from a surface cold front. On 12 November 2010, a split front was located over north-central Europe (Fig. 7). According to this model the trailing edge of the upper front is marked by sharply falling humidity aloft and sharp cloud boundaries on satellite images. The subsequent advance of the surface front is marked by low-level increases in clouds and often precipitation. In this case the cloud bands associated with surface and upper fronts are separated by approximately 200 km (Fig. 8). A *CloudSat* transect through a bright (low infrared temperature) cloud band reveals the vertical structure of the upper front (from 2 to 10 km) but little indication of precipitation at the surface. Surface-based radar composites at this time (not shown) confirm little or no precipitation in the vicinity of the *CloudSat* profile through the upper frontal band, but significant precipitation in the western half of Poland in the vicinity of the surface frontal band.

If the orientation of the transect is favorable, *CloudSat* can show detailed frontal structure over hundreds of kilometers. A Geocolor infrared image and *CloudSat* profile show a frontal cloud band off the West Coast of the United States (Fig. 9; 20 November 2009). Letter A (north) on the *CloudSat* profile shows orographic cloud enhancement (reds and yellows on the profile above elevated terrain) over the Cascade Mountains and Vancouver Island. On either side of point B farther to the south, the *CloudSat* profile reveals an elongated cloud composed of jet stream cirrus. Without a *CloudSat* profile a meteorologist might infer deep cloud and precipitation along this axis. At point C, *CloudSat* samples the eastern portion of a convective complex to the west of the frontal band. At point D to the south, *CloudSat* profiles the low-level frontal band, revealing cloud heights at about 4 km.

CloudSat is useful in mountainous terrain especially when high clouds obscure orographic effects at low levels. On 20 October 2007 strong zonal flow prevailed across California. A cirrus feature associated with a jet streak appears over the Sierra Nevada in the Geocolor infrared image (Fig. 10; 20 October 2007). The *CloudSat* profile reveals two major cloud systems affecting the area: 1) clouds associated with the westerly jet streak aloft and 2) a lower layer

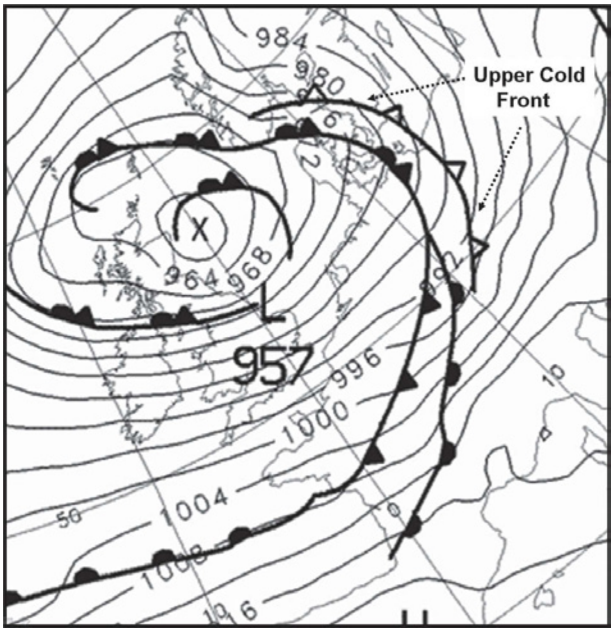


Fig. 7. Surface isobars (hPa) and frontal analysis over northern Europe, 0000 UTC 12 Nov 2010. Data and graphic from UK Met Office.

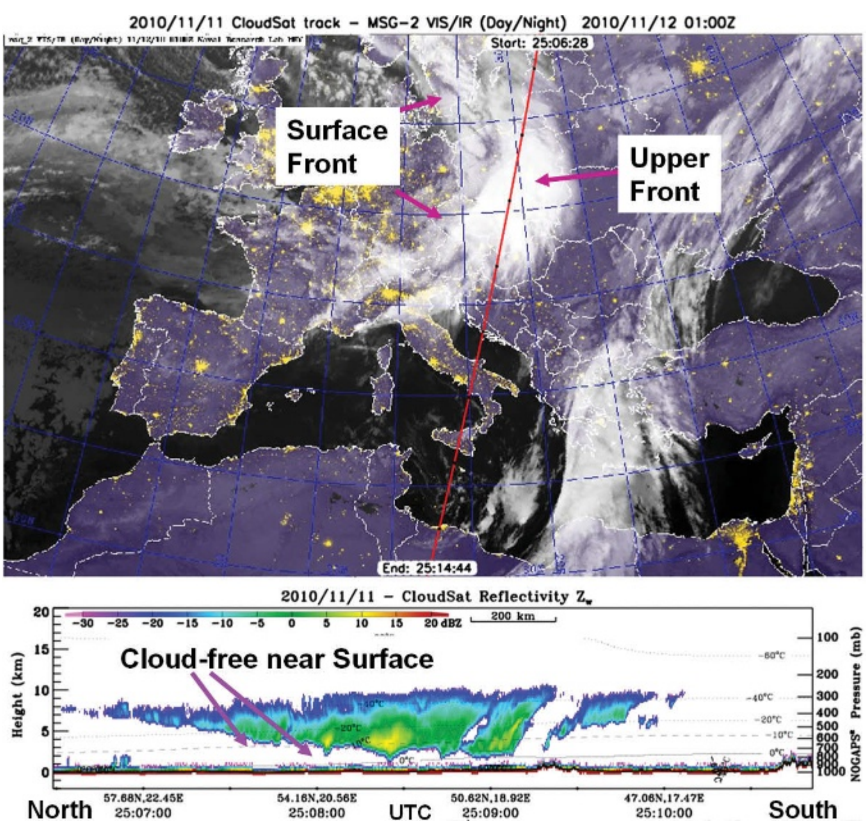


Fig. 8. (top) *Meteosat-8* Infrared Geocolor image, 0100 UTC 12 Nov 2010. Red line marks descending *CloudSat* overpass path. (bottom) *CloudSat* radar reflectivity profile.

underneath, composed of residual clouds following the passage of a weak cold front. The lower-level cloud is partly contained within the California Central Valley but slopes upward over terrain of the Sierra Nevada to the summit where it terminates.

Severe weather diagnosis. In general, heavy rain or hail attenuates the *CloudSat* signal near the ground sufficiently to obscure low-level cloud structure. However, "reflectivity spikes" are sometimes observed in the upper portions of convective cloud systems and serve as potential indicators of severe weather. On 2 December 2009, a strong cold front and associated convective cloud band brought severe thunderstorms and seven confirmed tornadoes over south-central Georgia, causing structural damage and injury (Figs. 11 and 12). The most intense convection appears in the *CloudSat* profile over northern Florida and Georgia with cloud tops generally around 12 km (Fig. 12). Also, at 31.5°N, an overshooting top appears that extends upward through the cloud system (resembles an upward pointing red arrow) with the top at approximately 14 km. This feature occurred very close (in time and space) to tornado reports and warnings in southeastern Georgia.

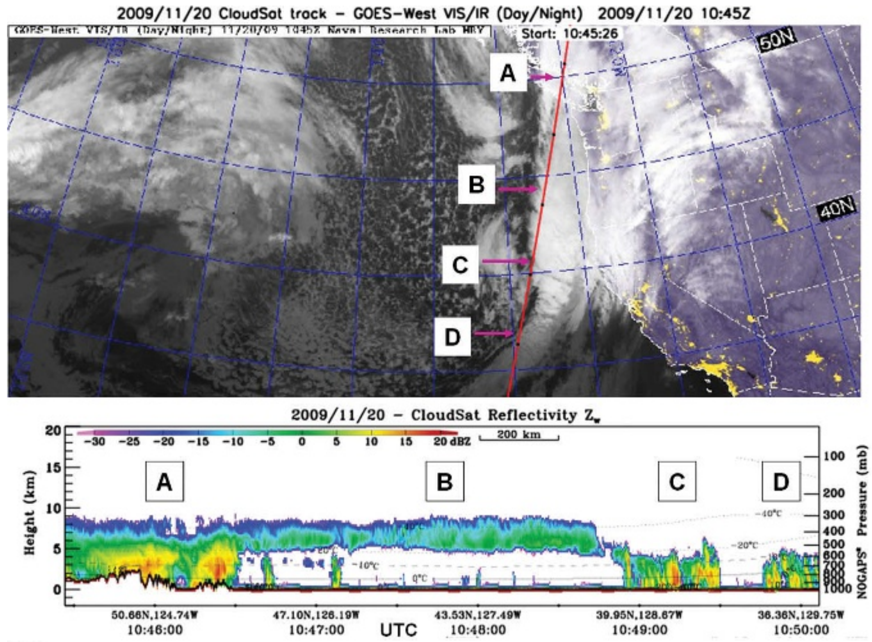


Fig. 9. (top) *GOES-11* Infrared Geocolor image, 1045 UTC 20 Nov 2009. Red line marks descending *CloudSat* overpass path. (bottom) *CloudSat* radar reflectivity profile.

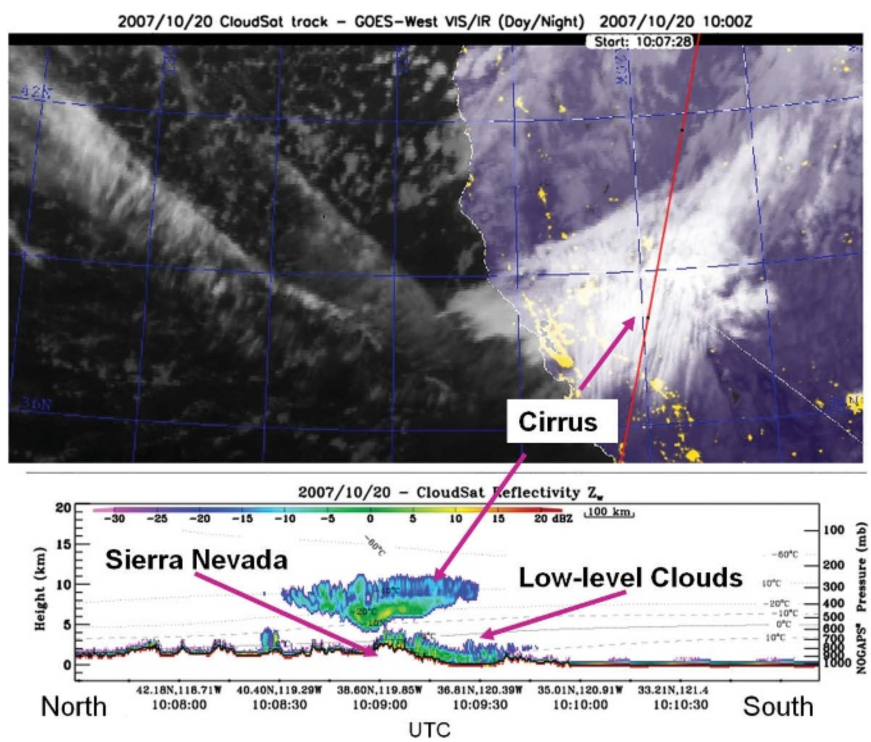


Fig. 10. (top) *GOES-11* Infrared Geocolor image, 1000 UTC 20 Oct 2007. Red line marks descending *CloudSat* overpass path. (bottom) *CloudSat* radar reflectivity profile.

Tropical cyclones. *CloudSat* helps delineate cloud structure in the core regions of tropical cyclones (Mitrescu et al. 2008). The profile displayed in Fig. 13 (15 September 2009) provides an example over Typhoon Choi-Wan, carrying maximum winds of about 125 kt. The prominent central eye becomes wider with increasing height in both the MODIS image from the *Aqua* satellite and the *CloudSat* profile. *CloudSat* reveals that the eye is cloud free over nearly the entire extent of the column, except that surface clutter prevents observation of lowest 1 km above the surface. The profile reveals information that the infrared image cannot. For example, on the northern side of the storm, precipitation is more stratiform, as revealed by the uniform melting layer at about 4 km. On the southern side, however, precipitation is characterized by a number of convective turrets. This example illustrates how the A-Train can constitute a "virtual satellite" with sensors on different satellites (*Aqua* and *CloudSat*) being easily colocated in time and space.

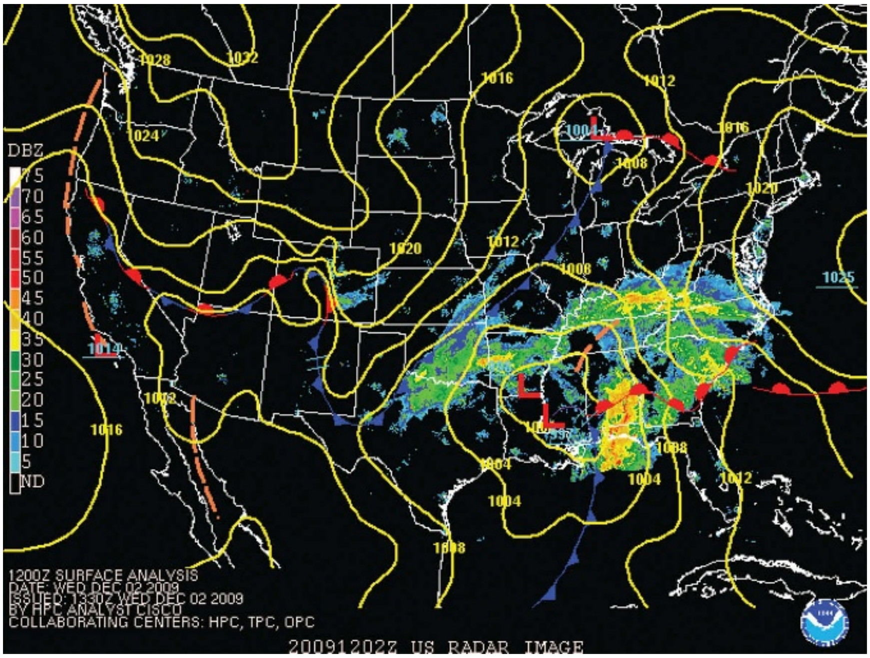


Fig. 11. Hydrometeorological Prediction Center (HPC) radar/weather depiction, 1200 UTC 2 Dec 2009. Courtesy of National Centers for Environmental Prediction (NCEP).

CloudSat can also be used to observe the periphery of tropical cyclones. AMSR-E precipitation retrievals (Kummerow et al. 2001; colors in Fig. 14) show heavy precipitation rates of approximately 1 inch per hour (25 mm h^{-1}) near the center of eastern Pacific Hurricane Celia (25 June 2010). Near the western periphery of the storm along the *CloudSat* overpass path, however, the precipitation rate drops to approximately 0.10 inches per hour (2.5 mm h^{-1}). Based on the AMSR-E/GOES product alone, forecasters might believe that the storm canopy is responsible for this precipitation. However, the *CloudSat* profile shows a large cloud-free gap between the canopy aloft (tops about 13 km) and a layer of stratiform clouds just above the surface (tops

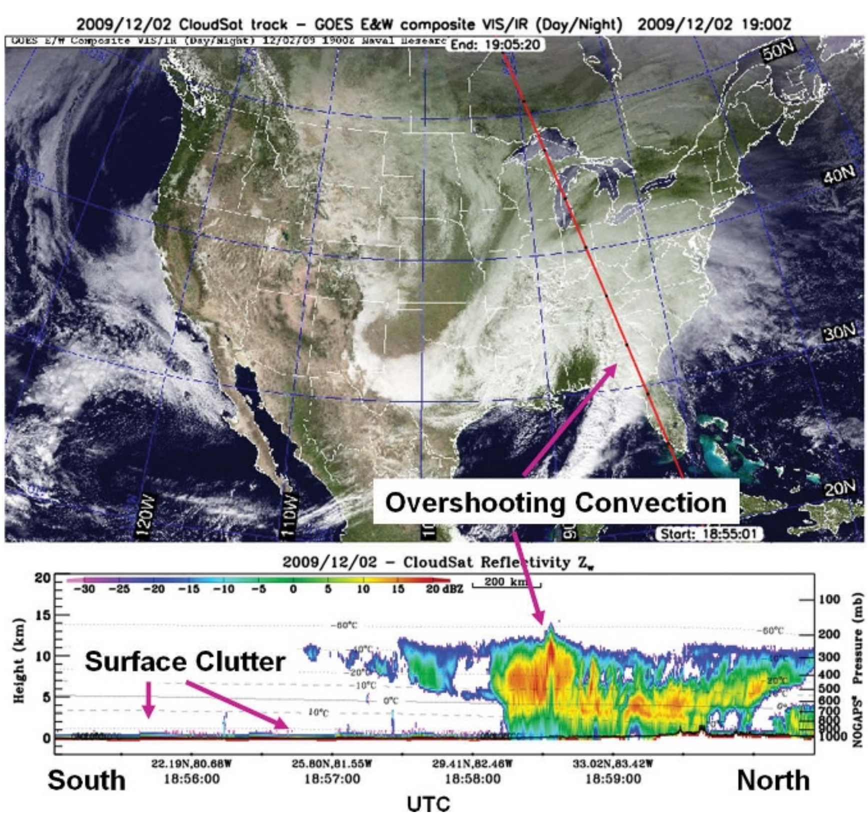
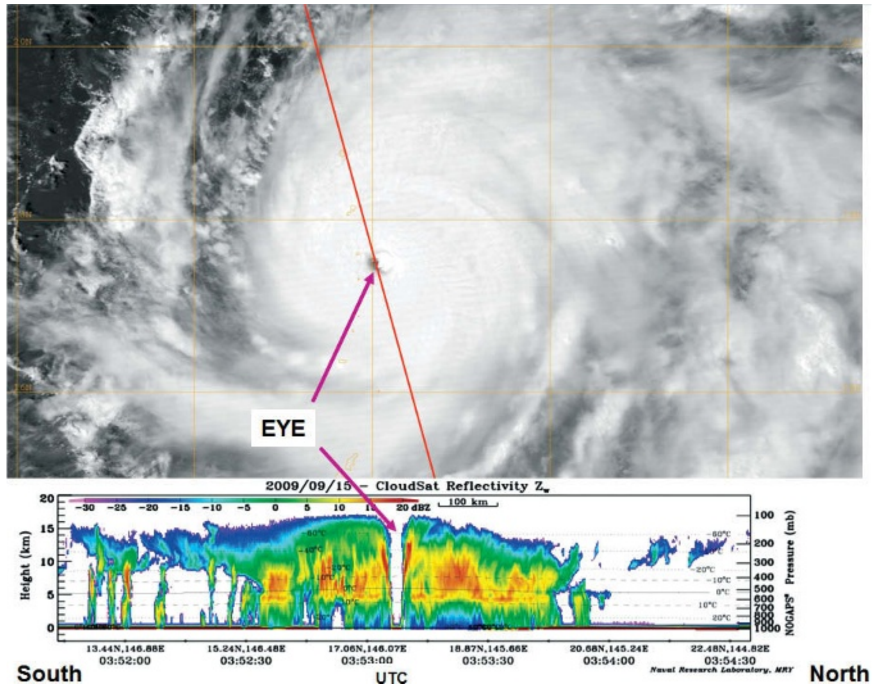


Fig. 12. (top) *GOES-11* infrared Geocolor image, 1900 UTC 2 Dec 2009. Red line marks ascending *CloudSat* overpass path. (bottom) *CloudSat* radar reflectivity profile.

Fig. 13. (top) *Aqua* MODIS visible image, 0355 UTC 15 Sep 2009. Red line marks ascending *CloudSat* overpass path. (bottom) *CloudSat* radar reflectivity profile.



at about 2.5 km). This critical information suggests that the lower layer is responsible for the precipitation observed by AMSR-E. Because of the demonstrated usefulness of microwave imagers to fix position and intensity (Hawkins et al. 2001; Lee et al. 2007), products like those shown in Figs. 13 and 14 are now used routinely by forecasters along with visible and infrared images. (See https://www.meted.ucar.edu/training_module.php?id=159.)

CONCLUSIONS. Within each class of phenomena there is endless variability, and the cases here are not presented as typical or representative. To promote the use of A-Train profiles in training materials, the profiles must be displayed in the context of other products such as satellite images, weather maps, and ground radar plots. Without this coupling, meteorologists will not be able to relate cloud vertical structure to the horizontal structure of weather systems.

With infrequent refresh over a specific area and a latency of several hours, *CloudSat* seldom captures evolving meteorological events in a way that could benefit forecasters.

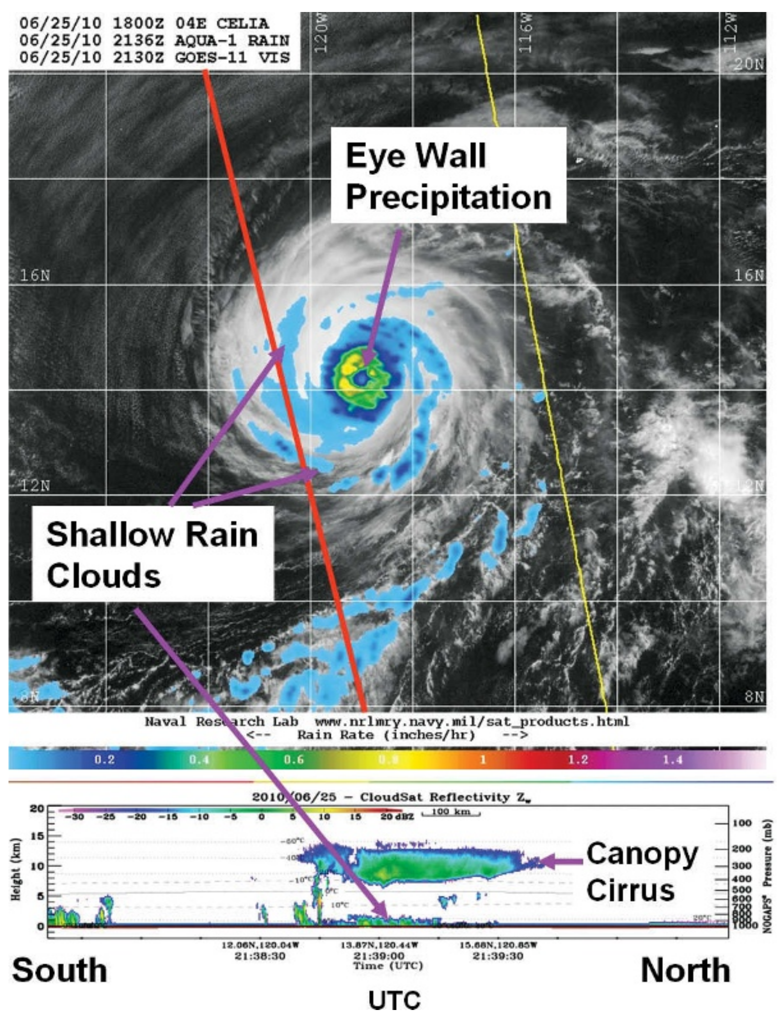


Fig. 14. (top) *GOES-11* infrared image in black and white, 2130 UTC 25 Jun 2010; corresponding AMSR-E precipitation rates (h^{-1}) in color. Red line marks ascending *CloudSat* overpass path. (bottom) *CloudSat* radar reflectivity profile.

However, data from future profilers may be delivered faster, enabling incorporation into the forecast process, especially poleward of about 50°N or S where temporal refresh increases. Even without real-time use, forecasters can greatly increase their knowledge of their area of responsibility by viewing profiler products from recent and historic weather events. They can gain insight into a number of phenomena. The stability of precipitation regions is one example. The meteorologist can acquire knowledge of the influence of orography on local cloud and precipitation patterns, relating upslope and downslope patterns to variations in wind flow and stability. Over oceans they can distinguish various types of cloud and precipitation regimes based on frontal type, cloud depth, and stability. *CloudSat* profiles over severe weather may supplement information from ground-based radar and other observations. Additionally, *CALIPSO* profiles of fog and stratus can provide accurate tops that are nearly impossible to infer from visible and infrared images. Stratus clouds are often assumed to be of uniform altitude; these profiles reveal important slopes that are important to understanding how fog and stratus evolve. The focus of this article was on midlatitude weather systems. A-Train profilers also have important applications for education and training in diverse regions, including the Arctic, the Antarctic, and the tropics.

ACKNOWLEDGMENTS. The authors gratefully acknowledge the support of the Joint Polar Satellite System (JPSS). Rafal Iwanski (Institute of Meteorology and Water Management, Krakow Poland) provided radar plots. Dr. Derek Posselt from the University of Michigan provided useful suggestions.

REFERENCES

Bretherton, C. S., and Coauthors, 2004: The EPIC 2001 stratocumulus study. *Bull. Amer. Meteor. Soc.,* **85,** 967–977.

Browning, K. A., and G. A. Monk, 1982: A simple model for the synoptic analysis of cold fronts. *Quart. J. Roy. Meteor. Soc.,* **108,** 435–452.

Hawkins, J. D., T. F. Lee, J. Turk, C. Sampson, J. Kent, and K. Richardson, 2001: Real-time internet distribution of satellite products for tropical cyclone reconnaissance. *Bull. Amer. Meteor. Soc.,* **82,** 567–578.

Kim, S.-W., E.-S. Chung, S.-C. Yoon, B.-J. Sohn, and N. Sugimoto, 2011: Intercomparisons of cloud-top and cloud-base heights from ground-based lidar, Cloudsat and CALIPSO measurements. *Int. J. Remote Sens.,* **32,** 1179–1197.

Kummerow, C., and Coauthors, 2001: The evolution of the Goddard profiling algorithm (GPROF) for rainfall estimation from passive microwave sensors. *J. Appl. Meteor,* **40,** 1801–1820.

L'Ecuyer, T. S., and J. Jiang, 2010: Touring the atmosphere aboard the A-Train. *Phys. Today,* **63,** 36–41.

Lee, T. F., and Coauthors, 2007: NPOESS online satellite training for users. *Bull. Amer. Meteor. Soc.,* **88,** 13–16.

Matrosov, S. Y., 2010: *CloudSat* studies of stratiform precipitation systems observed in the vicinity of the Southern Great Plains atmospheric radiation measurement site. *J. Appl. Meteor. Climatol.,* **49,** 1756–1765.

Miller, S. D., and Coauthors, 2006: NexSat: Previewing NPOESS/VIIRS imagery capabilities. *Bull. Amer. Meteor. Soc.,* **87,** 433–446.

Minnis, P., P. W. Heck, D. F. Young, C. W. Fairall, and J. B. Snider, 1992: Stratocumulus cloud properties derived from simultaneous satellite and island-based instrumentation during FIRE. *J. Appl. Meteor,* **31,** 317–339.

Mitrescu, C., S. Miller, J. Hawkins, T. L'Ecuyer, J. Turk, P. Partain, and G. Stephens, 2008: Near-real-time applications of CloudSat data. *J. Appl. Meteor. Climatol.,* **47,** 1982–1994.

——, T. L'Ecuyer, J. Haynes, S. Miller, and J. Turk, 2010: *CloudSat* precipitation profiling algorithm—Model description. *J. Appl. Meteor. Climatol.,* **49,** 991–1003.

Posselt, D., G. L. Stephens, and M. Miller, 2008: CloudSat: Adding a new dimension to a classical view of extratropical cyclones. *Bull. Amer. Meteor. Soc.,* **89,** 599–609.

Stephens, G. L., and Coauthors, 2002: The CloudSat mission and the A-Train: A new dimension of space-based observations of clouds and precipitation. *Bull. Amer. Meteor. Soc.,* **83,** 1771–1790.

Winker, D. M., M. A. Vaughan, A. Omar, Y. Hu, K. A. Powell, Z. Liu, W. H. Hunt, and S. A. Young, 2009: Overview of the CALIPSO mission and CALIOP data processing algorithms. *J. Atmos. Oceanic Technol.,* **26,** 2310–2323.

——, and Coauthors, 2010: The CALIPSO mission: A global 3D view of aerosols and clouds. *Bull. Amer. Meteor. Soc.,* **91,** 1211–1229.

USING A BUSINESS PROCESS MODEL AS A CENTRAL ORGANIZING CONSTRUCT FOR AN UNDERGRADUATE WEATHER FORECASTING COURSE

BY JOHN M. LANICCI

Seniors at Embry-Riddle University—many of them making their first weather forecasts—learn to see analysis and forecasting as both a scientific process and a business operation.

For the last five years, a business process model has been used as a central organizing construct for the senior-level Forecasting Techniques (WX 427) course at Embry-Riddle Aeronautical University's Daytona Beach, Florida campus. The Applied Meteorology Program has been granting undergraduate degrees since 2001, so it is a relatively young program with approximately 110 undergraduate majors and 180 minors. Embry-Riddle's undergraduate program offers five areas of concentration in aviation, media, commercial applications, computer applications, and research. Forecasting Techniques is a three-credit-hour course. It is normally taken second or third in a required four-course sequence that begins with Synoptic Meteorology (WX 356, an introduction to synoptic meteorology and computer applications). Forecasting Techniques can be taken either in conjunction with or after Advanced Weather Analysis (WX 456, a course that blends concepts from synoptic and dynamic meteorology and provides an introduction to mesoscale meteorology). The sequence ends with a capstone course, Weather Operations Seminar (WX 457), which introduces students to simulated and real-world forecast operational environments representative of various career paths that they may take upon graduation.

There are several motivations behind the business process model approach to teaching WX 427. The first is to provide a central organizing concept for the course. Because WX 427 is normally taken between

AFFILIATION: LANICCI—Applied Meteorology Program, Department of Applied Aviation Sciences, Embry-Riddle Aeronautical University, Daytona Beach, Florida
CORRESPONDING AUTHOR: John M. Lanicci, Applied Meteorology Program, Department of Applied Aviation Sciences, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, FL 32114
E-mail: john.lanicci@erau.edu

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-11-00016.1

In final form 3 December 2011

WX 356 and WX 457, the students typically enrolled in the class are seniors, the majority of whom are beginning to apply their knowledge from previous coursework as they learn to make their first weather forecasts. At this stage of their education, it is important that they develop the proper "mental models" of analysis and prediction, especially as various concepts start coming together in the forecasting process; the process model provides a template to facilitate this.

A second reason for employing a process model in this course is to prepare the students for WX 457, which goes beyond basic forecasting skills and often has students working on team projects that incorporate the "business operations" portion of weather analysis and forecasting. The process model used in WX 427 contains two major components: one focused on the technical aspects of weather analysis and forecasting and the other on user-focused business operations.

A third reason for using the process model is to provide an organizing framework for the students' final project, which is based on detailed analysis of a historical event that was influenced by the weather or climate or a historical weather event. The students are required to employ both portions of the concept model in their case-study analyses in order to understand the weather event and its impact on the affected region (e.g., population, infrastructure).

This paper provides a brief background on the use of process models to describe the weather forecasting enterprise, a history of the process model used in WX 427, and a description of how the model is applied in the course. The paper concludes with a brief assessment of the educational methodology employed in the course.

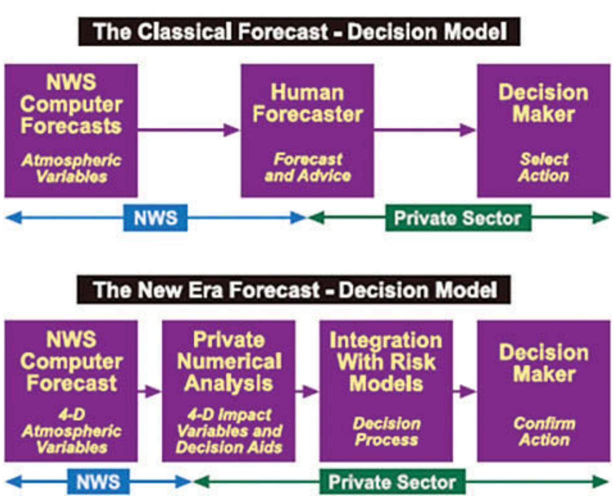


Fig. 1. The federal, private, and academic partnership in the atmospheric and climate sciences (from Dutton 2002).

USING PROCESS MODELS TO DESCRIBE WEATHER ANALYSIS AND FORECASTING.

According to Aguilar-Savén (2004), a business process is a combination of a set of activities within a business that describes the logical order of its activities and their dependence on one another. Business process modeling is a representation of those activities, which enables a common understanding and analysis of a business's key processes, deficiencies, and areas for process improvement. Aguilar-Savén reviewed a dozen methodologies for business process modeling, ranging from flowcharts to very structured techniques that can be translated into computer programs. Because industrial meteorology[1] often includes weather analysis and forecasting operations, it is not a great leap to adapt business process modeling techniques in order to improve our understanding of those operations.

Most of the business process models used to describe weather analysis and forecasting have been of the flowchart type. In fact, these models have been quite useful to illustrate the evolution of the forecasting process itself. Dutton (2002) employed two flowchart-type diagrams (his Figs. 4 and 5) to compare traditional approaches for incorporating weather information in user decision making with an emerging approach where standard meteorological information produced by the federal forecast centers is converted by private-sector firms into impact information and decision aids for integration into user decision-making processes. Dutton's Fig. 5 is reproduced here as Fig. 1 for convenience of illustration.

More recent examinations of the forecasting process have focused on the user of the information in an attempt to improve our understanding of how weather information is employed in decision making and how different types of information are employed by different user communities. Morss et al. (2008) proposed a flowchart-based process model as part of the societal and economic research and applications portion of the North American The Observing System Research and Predictability Experiment (THORPEX) program. Their model examined the dissemination of weather information (including its uncertainty), the use of decision support tools by users, and how

[1] Industrial meteorology, according to Glickman (2000), is defined as "the application of meteorological data and techniques to industrial, business, or commercial problems."

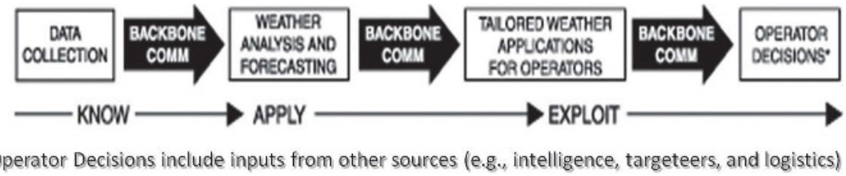


Fig. 2. Collection, analysis, and dissemination of weather information (from Lanicci 1998). The term "backbone comm" is used to show the presence of a robust global communications network that allows users at multiple levels of operations to have access to the same information.

the users' outcomes could be fed back to weather information providers through a mixture of traditional meteorological forecast verification measures and value added/relevance to the user (see their Fig. 1). A related THORPEX concept paper on communicating uncertainty by Brooks and O'Hair (2006) also employed a flowchart-based process model. Their model described the production of traditional meteorological information [e.g., numerical weather prediction (NWP) model forecasts]; interpretation by forecasters (including the forecast uncertainty); and the outcomes of that communication in terms of "economic value, personal safety, and trust" (see their Fig. 1). In both of these papers, the user's interpretation of translated forecast information and the outcomes of that interpretation were very important components of the process models. In the WX 427 process model, concepts such as dissemination, integration into decision making, and the provider–user relationship (PUR) are used to convey ideas that are similar to these studies, albeit in less detail.

The process model used in WX 427 originated with the U.S. Air Force (USAF). H. Massie et al. (1995, unpublished manuscript) described the processes of data collection, analysis, and forecasting; applications to warfighter models; and dissemination in a concept paper that advocated investments in remote sensing technologies that could provide observations in data-sparse areas. They argued that the observations obtained from these remote sensing platforms (data collection) would form the critical foundation for all the process actions to follow, such as improved regional-scale NWP model forecasts (analysis and forecasting). The output from the NWP model would be used to develop user-focused applications for predicting parameters such as cloud ceilings, surface visibilities, and flight weather hazards. This information would then be fed to weather effects decision aids (applications to warfighter models) that would identify the potential impacts of the predicted weather on both friendly and enemy forces. The resulting impacts information would be made available to all levels of military operations through the development of a robust global communications network of military and commercial systems (dissemination). This approach to depicting weather analysis and forecasting as a continuous process allowed USAF weather leadership to provide more quantitative estimates of weather information's value added to daily operations. Lanicci (1998) subsequently captured this sequential, one-way process graphically using a flowchart-based process model (shown in Fig. 2). The evolution of USAF weather analysis and forecasting operations into a more continuously updating process that included information integration into the user decision-making process was described by Lanicci (2003) and is reproduced here as Fig. 3. Note that these military-focused papers highlighted the importance of developing accurate and relevant user-focused decision tools in order to optimize their use of weather information, not unlike the process models discussed by Dutton (2002) and Morss et al. (2008).

The description of the business aspects of weather analysis and forecasting is not restricted to process

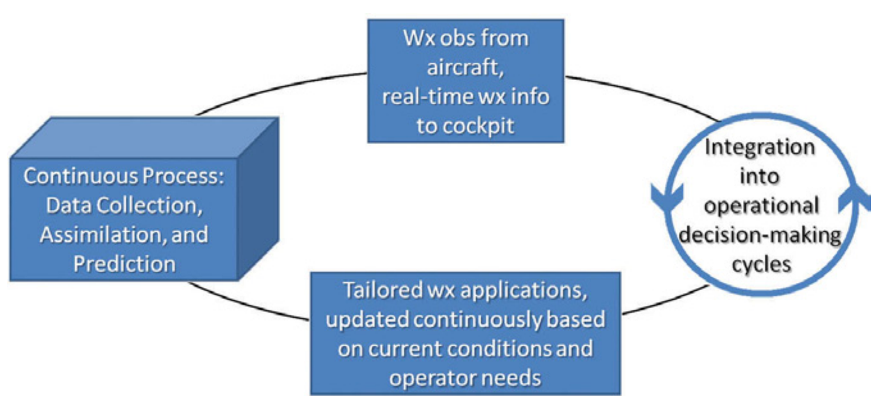


Fig. 3. Notional WIPC adapted from Lanicci (2003). The two-way information flow is shown by the thin black oval connecting the continuously updating functions of collection, assimilation, prediction, tailoring, and integration into decision making.

modeling approaches. A number of university programs have used several different techniques to incorporate the business operations portion of weather analysis and forecasting into their curricula, either directly or indirectly. Several examples of the differing approaches are presented here and are not intended to be all-inclusive. One method is a student-based forecasting-type operation in association with the department. Examples here include Penn State University's Campus Weather Service (http://cws.met.psu.edu/), the University of South Alabama's Coastal Weather Research Center (www.southalabama.edu/cwrc/index1.html), and the University of Wisconsin—Milwaukee's Innovative Weather (Roebber et al. 2010; http://innovativeweather.weebly.com/). Another method is to offer an "industrial meteorology" or "business/commercial" track as an option in the undergraduate curriculum, such as the University of South Alabama's Industrial Meteorology track and Embry-Riddle's Commercial Weather area of concentration. In these types of programs, students take courses outside the department, such as Marketing, Management, or specialized courses offered within the department. A third approach is unique and has been used by the University of Oklahoma for the last 14 years, known as the Master of Science in Professional Meteorology option (MSPM; see http://som.ou.edu/degrees.php?program=mspm). The program is geared toward students desiring a private-sector career and includes two distinctive aspects: 1) requirement for 12 credits of study in a secondary area and 2) student sponsorship/support by a private company, which includes an applied research project, normally chosen and supervised by the sponsor (Carr et al. 2002; Carr 2008).

APPLICATION OF THE BUSINESS PROCESS MODEL IN WX 427. The current version of the business process model employed in WX 427 is shown in Fig. 4. The model contains two primary but interrelated "tiers": 1) the weather information processing cycle (WIPC) and 2) the PUR. The process model expands several of the modules from the earlier USAF versions and adapts the symbology of business process modeling notation (BPMN) described by White (2004).

The WIPC is shown as a rectangle, meaning that it is "owned" by "process participants" (BPMN nomenclature). These process participants are primarily public-sector entities such as the National Centers for Environmental Prediction (NCEP) and its product centers for the modules through the tailored products phase. However, as in Dutton's model, there is also participation by private-sector interests in the tailoring, dissemination, and user integration phases. The process participants are not shown as separate entities as required by a strict interpretation of BPMN but are shown together as a "community of providers." This simplification is made so that topics such as division of responsibilities between public- and private-sector weather information providers can be introduced to students using the WIPC with minimal distraction from the symbology, while also illustrating that the public and private sectors can also partner. The individual process modules within the WIPC are shown by rounded rectangles, which denote activities (BPMN nomenclature), with the solid arrows denoting sequence flows (BPMN nomenclature) as data move through the production cycle and are transformed into useable information.

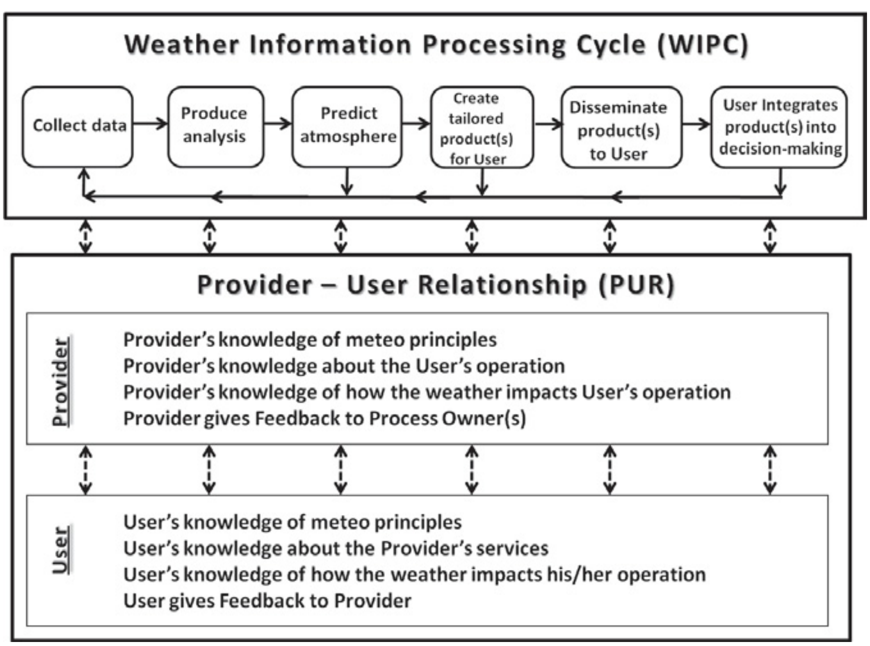


Fig. 4. Business process model employed in the Forecasting Techniques course. The top tier of the model labeled WIPC is described in the first part of WX 427. The bottom tiers entitled "provider" and "user" describe the PUR that is covered in the second half of the course.

In the PUR portion of the model, the provider and user are shown as process participants (in this case using separate rectangles to make distinctions between providers and users of meteorological information). The dashed arrows from user to provider and provider to WIPC process owner(s) denote message flows (BPMN nomenclature) between these groups, similar to the feedback processes proposed by Morss et al. (2008).

The process model is introduced to the students in multiple stages, beginning with collection, analysis, and prediction from the WIPC; transitioning to the PUR; and coming back to the WIPC modules of product tailoring, dissemination, and integration at the end of the course.

Collection, analysis, and prediction. The first three WIPC modules, shown in Fig. 3 as a cycle using the solid arrows, denote the traditional meteorological data production cycle operated at many centers around the world. The author spends the first three weeks of the course on this part of the cycle for two main reasons: 1) to familiarize the students with the data from the various observing platforms they will be using in making and verifying their forecasts and 2) to introduce the students to the structure and operation of NWP modeling systems run at national centers such as NCEP. To support the WIPC lectures, homework questions are developed from assigned readings taken from Persson (2007, hereafter P07), which includes sections on NWP model equations, physical processes, data assimilation, and forecast verification and is written at a level quite understandable by senior undergraduates. Of particular interest is the forecast verification section of P07, which discusses both traditional verification scores such as mean absolute error and more forecast value-added measures such as cost/loss ratio. The forecast verification section is utilized extensively in the PUR, tailoring, dissemination, and integration portions of the course.

By modularizing portions of the WIPC, the author is able to address various aspects of the analysis and forecasting operation and introduce students to some of the issues associated with them. For example, in the collection lectures, we discuss the importance of satellite-based soundings in improving the analysis and forecast quality of NWP models by using comparisons of data-coverage maps from different collection platforms obtained from the Met Office's four-dimensional variational data assimilation (4DVAR) scheme (for details, see http://research.metoffice.gov.uk/research/nwp/observations/data_coverage/index.html). The plots are shown to illustrate the uneven spatial distribution of rawinsonde, aircraft, and surface data observations compared to those from the Advanced Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (ATOVS) and the sheer quantity of observations available from satellite soundings compared to those from conventional sources. An accompanying 500-hPa height anomaly correlation time series from the European Centre for Medium-Range Weather Forecasts (ECMWF) NWP system, taken from Fig. 3 of Hollingsworth et al. (2002), is then shown to illustrate how the introduction of satellite-based soundings has closed the verification gap between the hemispheres and helped improve the quality of model forecasts in general.

The preceding collection discussion is a good segue to the analysis section, which employs the COMET module on data assimilation (available online at www.meted.ucar.edu/nwp/model_dataassimilation/) as a homework assignment and lecture tool in addition to P07, in order to introduce the students to the sophistication of today's NWP analysis systems. Although the intent of the analysis module is to give the students an appreciation for the complexity of data assimilation, it is just as important to give them some tools to evaluate the quality of model analyses and short-range forecasts. These quality check tools along with some suggested sources are listed in Table 1.

The prediction module takes the longest to complete. It is divided into multiple lectures along with a homework assignment on NWP. The lectures cover topics such as the history of NWP, model dynamics and physics, model postprocessing to include an introduction to model output statistics (MOS), and an intercomparison of operational models running at national centers such as NCEP. The lectures and homework are designed to give the students a qualitative appreciation for the complexity of the prediction model equations, physics parameterizations, and reasons for postprocessing raw model output. They also get introduced to the types of physical and dynamic features that a model can resolve as a function of its horizontal grid spacing and distribution of levels in its vertical coordinate system. One way to convey these differences in resolution is through comparing model depictions of topography in regions of complex terrain. An example comparing the Global Forecast System (GFS), North American Mesoscale model (NAM), and actual topography in Alaska is used in lecture because Anchorage International Airport (PANC) is one of the cities for which the students make forecasts.

Table 1. Suggested NWP model analysis quality check tools given to students in analysis module of WX 427.

Tool	Suggested sources (not all-inclusive)
Compare observations (surface, upper air, or both) with model-analyzed isobars and heights.	In house: NCEP Advanced Weather Interactive Processing System Map (NMAP) and General Meteorology Package Analysis and Rendering Program (GARP) plots of surface; upper-level observations overlaid with visible and/or IR imagery Web: California Regional Weather Server at San Francisco State University (http://virga.sfsu.edu/crws/press.html)
Compare the model-predicted variables (e.g., geopotential heights and vorticity) with satellite data in the early hours of the forecast cycle.	In house: NMAP animation of 6-h GFS; NAM forecasts of sea level pressure/thickness overlaid with visible and/or IR imagery; 500- and/or 300-hPa forecasts overlaid with water vapor imagery)
Compare model prediction with its own analysis (e.g., 18-h, 700-hPa forecast from GFS valid at 0600 UTC today compared to the GFS 0600 UTC analysis).	In house: NMAP and GARP overlays Web: NCEP Central Operations (http://mag.ncep.noaa.gov/NCOMAGWEB/appcontroller)
Compare analysis fields of two different models (e.g., 700-hPa analysis from GFS and NAM).	In house: NMAP and GARP overlays Web: NCEP Central Operations (http://mag.ncep.noaa.gov/NCOMAGWEB/appcontroller)

analogues, and the forecast funnel (Snellman 1982). It is emphasized that an operational forecast often combines features of these techniques. It is also at this stage where the students begin making their first set of weather forecasts, a series of five city pairs for Daytona Beach and a second location out of the conterminous United States (CONUS). The list of cities and forecast parameters is shown in Table 2. These city-pair forecasts give the students an opportunity to put into practice what they learned in the first three WIPC module lectures and homework. For example, in the collection lectures, students are introduced to the operation of the Automated Surface Observing System (ASOS) and examine the observing procedures from OFCM (2005), particularly with respect to the FMH

The prediction module concludes with an introduction to forecasting techniques such as persistence/modified persistence (important in Florida, especially during the wet season), climatology,

Table 2. WX 427 list of cities and forecast parameters from spring 2010 semester.

Locations	Date	Parameters
Daytona Beach and Frankfurt, Germany (practice exercise)	Monday, 22 Feb in class [due no later than (NLT) midnight 22 Feb] Forecast for Wednesday, 1200 UTC 24 Feb	Temperature, dewpoint (both in °F), wind direction (10° increments) and speed (kt), sea level pressure (whole hPa), and WX = Y/N*
Daytona Beach and Frankfurt, Germany (exercise 1)	Friday, 26 Feb in class (due NLT midnight 26 Feb) Forecast for Sunday, 1200 UTC 28 Feb	Same as practice exercise
Daytona Beach and Anchorage, Alaska (exercise 2)	Wednesday, 3 Mar (due NLT midnight 3 Mar) Forecast for Friday, 1200 UTC 5 Mar	Same as practice exercise
Daytona Beach and Tokyo, Japan (Narita Airport) (exercise 3)	Monday, 8 Mar (due NLT midnight 8 Mar) Forecast for Wednesday, 1200 UTC 10 Mar	Same as practice exercise
Daytona Beach and London, UK (Heathrow Airport) (exercise 4)	Monday, 22 Mar (due NLT midnight, 22 Mar) Forecast for Wednesday, 1200 UTC 24 Mar	Same as practice exercise
Daytona Beach and Sydney, Australia (exercise 5)	Monday, 29 Mar (due NLT midnight 29 Mar) Forecast for Wednesday, 1200 UTC 31 Mar	Same as practice exercise

* WX = Y/N refers to the binary yes or no forecast of whether surface visibility will be <7 miles and/or precipitation will be observed at the airport (WX = Y) or the surface visibility will be ≥7 miles with no precipitation (WX = N).

visibility reporting procedures. This part of the FMH becomes particularly relevant in the "WX = Y/N" portion of the exercises described in Table 2. The formulation of this forecast criterion forces the students to pay close attention to the observational data and not become totally reliant on the NWP products and MOS guidance. Additionally, the WX = Y/N parameter is used to illustrate the difficulties associated with making a "binary" forecast decision, which often frustrates both students and instructor alike when the forecast does not verify. The author subsequently builds upon this binary forecast experience in the second part of the course, when the students are introduced to making probabilistic-type forecasts.

Provider–user relationship. The purpose of the PUR is to show that the relationship between providers and users of meteorological information has certain aspects that both sides need to understand and that this relationship can in turn affect the execution of the WIPC through user requirements (e.g., new observational data needs) and product feedback such as forecast verification statistics and value-added performance metrics. Within the PUR, we examine concepts pertaining to this relationship from the points of view of both the provider and user. These topics, summarized in Table 3, include several that are not traditionally covered in introductory forecasting courses, such as user-requirements analysis. It has been the author's experience that proper development

Table 3. WIPC/PUR module topics covered in the second part of WX 427.

Module	Topics
Provider's knowledge of meteorological principles (PUR)	• Atmospheric scales of motion and how to apply to forecasting · Interactions between Florida sea-breeze circulations and synoptic-scale pressure gradient • Application of climatology to forecasting · Use and interpretation of frequency distributions • "Phenomenology" such as local effects and types of weather typically observed in a location
Provider's knowledge about the user's operation (PUR)	• How weather/climate impact the user's business operations • Knowledge of user requirements · Distinguishing between user requirements (general needs), specifications (specific types of information, how often, etc.), and provider's capabilities • How to convey your limitations to the user
User's knowledge of meteorological principles (PUR)	• Types of users and how they use weather information · General public · "Specialized" users (e.g., aircrews) · Users who are also providers (e.g., other forecasters, air traffic controllers)
User's knowledge about the provider's services (PUR) User's knowledge of how weather/climate impacts operations (PUR)	• Knowledge of how weather/climate impact business • Requirements for weather/climate services from the provider • Knowledge of provider's capabilities and limitations • Defining the user's "mission space" · Resource protection, risk mitigation, exploitation of weather versus adversary/competitor
Dissemination of tailored weather products to the user (WIPC)	• Dissemination technologies · Handheld devices and real-time notification of significant weather
Integration of weather information into user decision-making process (WIPC)	• Examples of weather organizations that are well integrated into user decision process · 45th Weather Squadron field trip

of user requirements is a very complex process for which many scientific professionals are unprepared when they move into technical management positions later in their careers.

At this point, it would be useful to explain why the PUR is covered before the product tailoring, dissemination, and integration modules in the WIPC. There are three reasons: 1) Establishing the types of tailored weather information products needed by users is determined by analysis of the user's requirements. 2) The method of weather product dissemination is also largely determined by the user's requirements. 3) Integration of the weather information into the user's decision-making process is usually part of the user's business practices. In order to understand the latter part of the WIPC then, it is better to cover the PUR first. This portion of the course also marks the transition from the city-pair forecasts to a second set of forecasting exercises that reinforces the concepts taught in this phase of the course.

The PUR begins with a series of lectures on the types of meteorological knowledge that a provider needs in order to understand fully and satisfy the requirements of the user. This includes topics such as scales of motion; applications of descriptive, dynamic, and applied climatology; and knowledge of local effects/phenomenology. In-class examples are often used to cover several of these areas simultaneously. A good illustration is the Florida sea-breeze circulation. In the WIPC, the sea-breeze phenomenon was used as an example of the limitations in NWP model reproduction of mesoscale features, incorporating portions of the COMET sea-breeze module (available online at www.meted.ucar.edu/mesoprim/seabreez/index.htm). In the PUR, the Florida sea-breeze circulation is used to examine the interaction between processes operating on the synoptic scale and mesoscale in the scales-of-motion lecture but also as an example of local effects and phenomenology knowledge that a forecaster must have. The sea-breeze phenomenon is a very useful teaching tool in the course because the lecture materials are reinforced through forecasts for Daytona Beach International Airport (KDAB) and the National Weather Service (NWS) Melbourne forecast office's area of responsibility in east-central Florida.

The PUR discussion continues with an examination of the relationship between providers and users. Here, the author asks the question, "What does the provider need to know about the user?" This leads to discussion of the types of users of meteorological information, weather "salience" of the user (see Stewart 2009), determining how the weather and/or climate impact the user's business operation and how to determine user requirements and convey the provider's limitations to the user. In class, the author gives students examples of vague and specific user requirements, requirements that sound more like "solutions," and unrealistic requirements (i.e., going beyond the provider's capabilities) and asks the students to distinguish among them.

The "flip side" of the PUR is examined with the question, "What does the user need to know about the provider?" In this section, the class covers points about determining the meteorological knowledge of users, how much users can articulate about how weather and/or climate impact their business operations (i.e., whether they have quantitative impact data or anecdotal experiences only), and how users may convey their requirements for weather and/or climate services to the provider (e.g., "I do not know what I need. What do you have?"). The author emphasizes the importance of ensuring the user understands the provider's capabilities and limitations, especially during the requirements analysis portion of developing their business relationship.

The PUR section closes with an illustration of one method for determining user requirements, by categorizing his/her "mission areas." This essentially involves examining the user's weather and/or climate sensitivities and needs in three domains: 1) resource protection; 2) risk mitigation; and 3) exploitation. Resource protection is defined as the traditional mission of protecting life and property. Risk mitigation is defined here as "sustained action taken to reduce or eliminate long-term risk to people and their property from hazards and their effects" [taken from the Federal Insurance and Mitigation Administration, a division of the Federal Emergency Management Agency (FEMA); see www.fema.gov/about/divisions/mitigation.shtm]. Exploitation is presented as an emerging area of support to business and military users. It is distinguished from risk mitigation by examining the user's weather and/or climate sensitivities vis-à-vis a competitor, in order to determine if there are weather and/or climatic situations that the user can exploit to his/her advantage, at the expense of the competition. This portion of the course uses several hypothetical as well as historical examples to illustrate these ideas and emphasizes that there is nearly always a significant overlap among the three mission areas.

Product tailoring, dissemination, and integration into user decision making. The PUR and WIPC are linked when we examine how different types of users (e.g., general public, businesses, aviation, and the military) employ tailored weather information and sophisticated dissemination technologies to integrate the information into their decision-making processes. At this stage of the course, the students are introduced to a new set of real-time forecasting exercises. These exercises give the students, now working in teams, experience preparing different types of tailored weather forecasts, varying from synoptic-scale products similar to those of the Hydrometeorological Prediction Center (HPC) to local forecasts for a hypothetical weather-sensitive customer. These exercises are summarized in Table 4. Although only the fourth type of forecasting exercise is totally linked to the PUR, the introduction of probability-based forecasts in exercise types 2 and 3 gives the students an appreciation of how a user would employ this type of information as opposed to the binary yes/no employed in the city pairs. At the completion of these last four exercises, the students are now prepared for the types of team-based projects they will execute in WX 457.

Table 4. Forecasting exercises used during the second half of WX 427.

Forecast type	Verification method
Type 1: Continental U.S. forecast chart of sea level pressure, highs, lows, fronts, troughs, precipitation areas, types, and intensities, patterned after the NCEP HPC	Subjective, using HPC analysis, radar summary, and weather depiction charts for valid time
Type 2: Forecast for east-central Florida area, patterned after the graphical product from the NWS forecast office in Melbourne: variables are temperature, dewpoint, and probability of precipitation for two specific times	Subjective, using plotted and analyzed surface observations and regional radar summary for valid times, and objective, using mean absolute error scores and Brier scores for selected stations
Type 3: Point forecast KDAB using hourly weather graph format from the NWS forecast office in Melbourne; variables are temperature, dewpoint, wind direction/speed, and probability of precipitation over a 24-h period	Objective, using mean absolute error from KDAB observations and Brier score for probability of precipitation
Type 4: Forecast for a weather-sensitive customer, usually an outdoor event at a specific location for multiple time periods: variables are usually probability of measurable precipitation; probability of accumulated precipitation above a specified threshold; and/or probability of occurrence of thunderstorms, snow, etc.	Objective, using Brier score and Brier skill score for comparison against climatological probabilities: cost–loss calculations after P07

To drive home the point about being integrated into the user's decision-making process, the class goes on a field trip to the USAF's 45th Weather Squadron operations center at Cape Canaveral Air Force Station. This visit consists of a mission briefing; tours of the Applied Meteorology Unit and operations floor, complete with product demonstrations; and a briefing on how to develop tailored products that are timely, relevant, and useable for real-time decision making. The trip allows the students to get a first-hand look at how tailored weather decision guidance is integrated into the decision-making process for space launches.

ASSESSMENT OF THE EDUCATIONAL METHODOLOGY EMPLOYED IN WX 427.

The breakdown of grading in WX 427 has historically been a 50–50 split between forecasting exercises and homework/final project. This is done because the course is a combination of traditional lecture, homework, and forecast practicum, and the intent is for the students to learn about the forecasting enterprise by applying the WIPC/PUR business process model throughout the semester. In order to assess the effectiveness of the WIPC/PUR model as a teaching tool, the author used several methods. First, the author examined how well the students applied the WIPC/PUR model in their final projects by looking at the project grading distribution over the past eight semesters.[2] Within this sample, the author also compared the grades for the four most commonly chosen project topics and looked for similarities and differences between them and the rest of the project topics. Second, the author investigated the results of end-of-course evaluations, paying particular attention to student ratings on course organization, clarity of objectives, and the overall evaluation of the course, these being a reflection of using the WIPC/PUR model as an organizing construct.

The final project consists of a written paper and an oral presentation, in which the students are instructed

[2] The results from the fall semester 2006 were excluded from this study because this was the first time the author taught the course, and it was restructured into its present form in spring semester 2007.

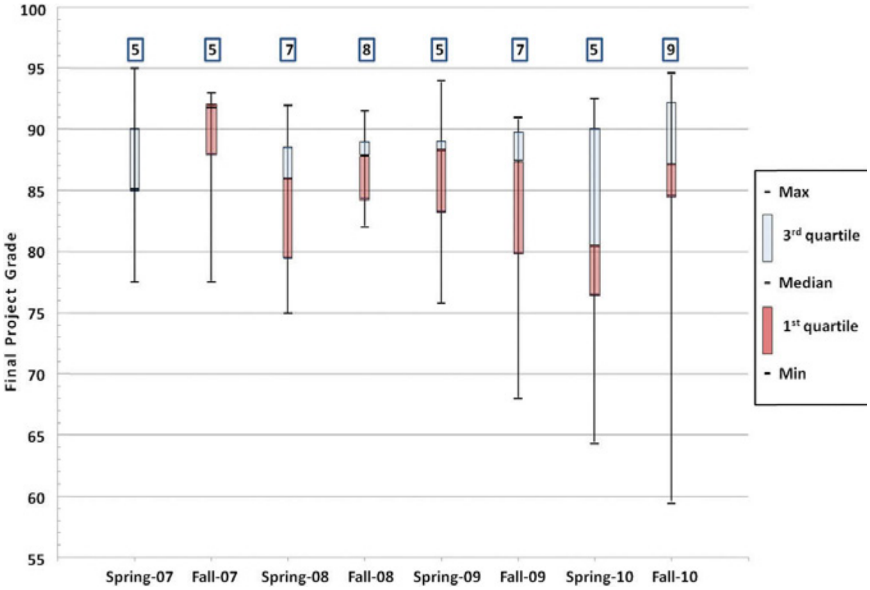


Fig. 5. Timeline graph showing final-project grading distribution for WX 427. The boundary between the blue and red columns denotes the median class grade. The numbers enclosed by boxes above each plot denote the number of student teams for that semester.

to apply the principles of the WIPC and PUR that they learned throughout the course. Specifically, they are asked to describe which portions of the WIPC were most relevant to their case and how well they worked and to evaluate the PUR in terms of areas such as provider knowledge of the user and user weather knowledge and awareness. Specific examples from historical events are used to illustrate aspects of the WIPC and PUR as a means of providing project guidance. For example, the WIPC processes of collection, analysis, prediction, and integration were most important for the D-Day invasion because the Allies' superior observational data availability over the northeast Atlantic Ocean led to a better analysis and forecast on the Allied side versus the German side. This forecast was effectively integrated into planning and execution to achieve the surprise necessary for the invasion's success. A standard PUR example used in class is the relationship among forecasters, engineers, and National Aeronautics and Space Administration (NASA) decision makers in the Space Shuttle *Challenger* accident. We discuss the lack of communication and improper integration of weather into the decision-making process that led to the tragedy (among several lessons that are reinforced during the 45th Weather Squadron field trip). When the students apply the WIPC/PUR model properly to their case studies, this is reflected in their project grades.

The final-project grades from spring semester 2007 through fall semester 2010 are shown in a box-and-whisker timeline plot (Fig. 5). The majority of project scores typically ranged from the upper 70s to the lower 90s. The mean grade over this period was 85.5 with a standard deviation of 7.4; there were 51 total projects encompassing 109 students. This result suggests that the majority of students were achieving a reasonable understanding of the WIPC/PUR model as it applied to their final-project cases. However, Fig. 5 also shows an increase in the range of grades after fall semester 2008, with an increase in the number of project grades below 70 during the last three semesters. The project guidance remained relatively unchanged throughout this period with one notable exception. Beginning with fall semester 2008, the term paper due date was changed to three weeks earlier than in previous semesters. This change was made to give students the opportunity to make revisions prior to the end of the semester; the presentation dates remained unchanged. The rationale was that the review and revision process would provide a valuable learning experience, potentially leading to a final written product suitable as a writing sample for prospective employers. However, it is quite possible that the

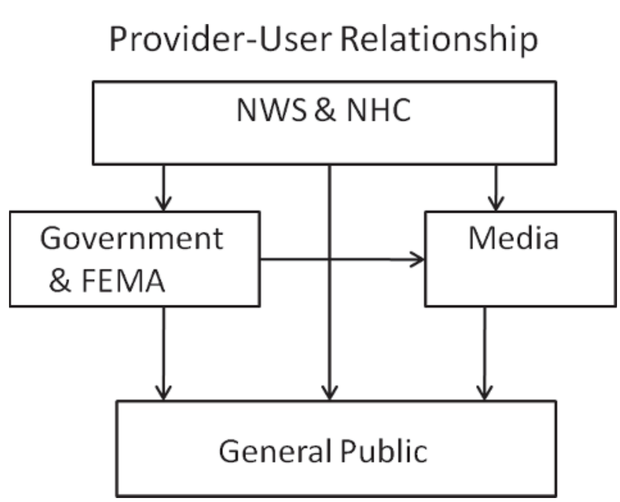


Fig. 6. Student representation of PUR during Hurricane Katrina.

earlier due date resulted in some students having an incomplete grasp of the WIPC and PUR, with the revision process becoming more of a "dot the i's and cross the t's" exercise than a true manuscript revision. The mean project grade/standard deviation before the due-date change was 86.3/5.9; after the change it was 85.1/8.2. The author ran a *z* test on the grading data from before and after the due-date change; the test results showed that the means did not differ significantly. However, it is entirely plausible that an inability to grasp the WIPC/PUR concept fully, combined with the amount of revision to an already problematic paper, may have been too challenging for some students given the limited time for revisions (~1–2 weeks) at the end of the semester. The paper revision policy may need to be revisited.

The author performed an additional analysis of student projects from the four most popular topics: Hurricanes Andrew and Katrina (each chosen four times), space weather (chosen three times), and the Groundhog Day 2007 tornado outbreak in central Florida (chosen three times). This review encompassed 14 projects (33 total students) and allowed for some "common ground" upon which to judge student performance; the sample included projects from before and after the due-date change. The grades for these groups ranged from 75 to 95, with a mean/standard deviation of 87.0/6.1, close to the overall project average/standard deviation of 85.5/7.4. There was some good student ingenuity in these case studies; two examples from the Hurricane Katrina projects are worth noting. One group suggested that the WIPC be used as a planning tool for future events to identify areas of potential breakdowns between the provider and user communities, whereas another group built their own information flow diagram of the PUR for this case (shown here as Fig. 6). The student PUR diagram is particularly insightful in that it illustrates several sources of weather information for the general public (e.g., NWS, various levels of government, and the media). Despite the dissemination of dire warnings from the NWS, a mandatory order to evacuate New Orleans was not given until less than 24 h before landfall (U.S. House of Representatives 2006). In this case (and illustrated in Fig. 6), multiple information providers could be a source of confusion depending on the message, thus affecting the ability of users to act on the information.

Finally, the student evaluations for the last eight semesters were examined, with particular attention paid to questions about course objectives, organization, and overall satisfaction. Unfortunately, the university changed the course evaluation questions after fall semester 2008, so analogous questions were used to determine student reaction to the course's statement of objectives and its organization. Table 5 shows a listing of the evaluation questions along with

Table 5. Student end-of-course evaluation ratings for WX 427 course objectives and organization.

	Almost always	Often	Infrequently	Almost never	
1) The instructor made the course objectives clear (spring 2007–fall 2008); The learning outcomes were clearly stated (spring 2009–present).	72.1%	27.9%	0.0%	0.0%	
2) The instructor organized and presented the course material effectively (spring 2007–fall 2008); The instructor taught the course content in a manner that made it understandable (spring 2009–present).	72.1%	25.6%	2.3%	0.0%	
(Spring 2007–fall 2008)	**Excellent**	**Above average**	**Average**	**Below average**	**Poor**
3) Considering everything, I would rate the instruction in this course.	56.5%	37.0%	6.5%	0.0%	0.0%
(Spring 2009–present)	**Strongly agree**	**Agree**	**Disagree**	**Strongly disagree**	
3) I am satisfied with the instruction in this course.	82.1%	17.9%	0.0%	0.0%	0.0%

the response rates. Generally speaking, the students approve of the way in which the objectives have been presented and organized, with over 70% of the 86 respondents rating the objective/organization in the highest category (questions 1 and 2 in Table 5). The results for the overall rating are also encouraging, with over 90% of student respondents rating the course as above average/excellent and over 80% strongly agreeing that they were satisfied with the course instruction (question 3 in Table 5).

CONCLUSIONS. This paper presented a business process model for the weather forecasting enterprise that encompasses both its technical and business operations aspects. The model, adapted from the USAF, is similar to flowchart process models used by Dutton (2002) to describe the transition of the weather forecasting enterprise and those of Morss et al. (2008) and Brooks and O'Hair (2006) that focused on the users of weather information and the outcomes of their usage. The primary purpose of the model in the course is as a central organizing construct, helping students bring together various concepts from their previous coursework and to prepare them for the simulated operations of the Embry-Riddle Applied Meteorology Program's capstone course.

In particular, the importance of the PUR portion of the model cannot be overlooked. It is vitally important for the weather information provider, especially if he or she is in a business–client relationship with a user, to understand user requirements, expectations, and subject-matter grasp of weather and climate. The PUR is also a useful tool for defining roles and relationships within a specific type of operation. For example, as this paper goes to press, a considerable amount of analysis and testing is being done to define policies for production and usage of aviation weather information in the four-dimensional data cube being defined by the Next Generation Air Transportation System program (see, e.g., the summary of the 2011 Friends and Partners of Aviation Weather Summer Meeting, particularly the last session, entitled "Building the SAS, policy and governance challenges": available at www.ral.ucar.edu/general/Summer_Meeting_2011/).

Assessment of the concept model gave generally good results, as evidenced by above-average final-project grades using the WIPC/PUR model as the analysis template. However, the idea of allowing term paper revisions by changing the deadline to an earlier date appears to have mixed results in that some students may not have fully grasped the WIPC/PUR concept until the end of the semester. One of the ideas being considered is to move some of the PUR material into WX 457, where it may be a better fit with that course's objectives, allowing the students to concentrate more on the technical aspects of the analysis and forecasting process in WX 427.

Although the WIPC/PUR model is a useful teaching tool in this course, its adaptation by educators in other meteorology/atmospheric science programs should be tempered by examining the context within which they intend to use it. This model was helpful in WX 427 because the course is a "waypoint" between the beginning synoptic meteorology course and the weather operations seminar in Embry-Riddle's program. Programs with more than one forecasting course (e.g., practicums, current weather discussions) should evaluate the use of this model only after considering the differences between the way it has been used here and how it may be employed elsewhere.

The usefulness of the model to teach students how to forecast has not been fully evaluated. There are four years of city-pair forecast data that can be analyzed statistically to determine if there is student forecaster learning taking place and to what extent. This type of analysis would be quite useful in linking course objectives with outcomes, in addition to those presented here, and is being considered for future investigation.

ACKNOWLEDGMENTS. I would like to thank several key individuals and groups for their help during the development of the business process model and its application in the undergraduate curriculum at Embry-Riddle. Discussions with Drs. Fred Mosher, Chris Herbster, Thomas Guinn, and Randell Barry in the Applied Meteorology Program were most helpful as I began adapting the model from USAF weather operations to the undergraduate classroom. The students who took the course provided valuable feedback both during as well as after the class for improving the model, the forecasting exercises, homework assignments, and the final project. I learned a great deal from 51 different team presentations covering 35 topics, ranging from the effects of weather on the sinking of the *Titanic* to discussions of the PUR in the *Challenger* disaster. The PUR diagram shown in Fig. 6 was originally developed by two of my students, Audrey Kiefer and Marissa Gonzales, and I would like to take this opportunity to acknowledge their ingenuity. I would also like to thank the three anonymous reviewers, whose comments and suggestions for improving this paper were extremely helpful.

REFERENCES

Aguilar-Savén, R. S., 2004: Business process modelling: Review and framework. *Int. J. Prod. Econ.,* **90,** 129–149.

Brooks, H. E., and D. O'Hair, 2006: Communication of uncertainty. Preprints, *North American THORPEX Societal and Economic Research and Applications Workshop,* Boulder, CO, NCAR, 25 pp. [Available online at www.sip.ucar.edu/thorpex/pdf/NAT_SERA_Theme_Paper_1_Brooks.pdf.]

Carr, F. H., 2008: The M.S. in Professional Meteorology degree program at the University of Oklahoma: A partnership between academia and the private sector. Preprints, *CCM Forum,* New Orleans, LA, Amer. Meteor. Soc., 1.4.

——, K. K. Droegemeier, and J. F. Kimpel, 2002: A new M.S. in Professional Meteorology degree program at the University of Oklahoma. *11th Symp. on Education,* Orlando, FL, Amer. Meteor. Soc., 4.8.

Dutton, J. A., 2002: Opportunities and priorities in a new era for weather and climate services. *Bull. Amer. Meteor. Soc.,* **83,** 1303–1311.

Glickman, T. S., 2000: *Glossary of Meteorology.* Amer. Meteor. Soc., 855 pp.

Hollingsworth, A., P. Viterbo, and A. J. Simmons, 2002: The relevance of numerical weather prediction for forecasting natural hazards and for monitoring the global environment. European Center for Medium-Range Weather Forecasts Tech. Memo. 361, 29 pp. [Available online at www.ecmwf.int/publications/library/ecpublications/_pdf/tm/301-400/tm361.pdf.]

Lanicci, J. M., 1998: Integrating weather exploitation into airpower and space power doctrine. *Airpower J.,* **12,** 52–63..

——, 2003: Weather operations in the transformation era. Air War College Maxwell Paper 29, 35 pp. [Available online at www.au.af.mil/au/awc/awcgate/maxwell/mp29.pdf.]

Morss, R. E., J. K. Lazo, B. G. Brown, H. E. Brooks, P. T. Ganderton, and B. N. Mills, 2008: Societal and economic research and applications for weather forecasts. *Bull. Amer. Meteor. Soc.,* **89,** 335–346.

OFCM, 2005: Federal meteorological handbook No. 1: Surface weather observations and reports. Office of the Federal Coordinator for Meteorological Services and Coordinating Research Rep. FCM-H1-2005, 104 pp. [Available online at www.ofcm.gov/fmh-1/pdf/FMH1.pdf.]

Persson, A., 2007: User guide to ECMWF forecast products. European Center for Medium-Range Weather Forecasts Meteorological Bulletin M3.2, Version 4.0, 127 pp. [Available online at www.ecmwf.int/products/forecasts/guide/user_guide.pdf.]

Roebber, P. J., M. Westendorf, and G. R. Meadows, 2010: Innovative weather: A new strategy for student, university, and community relationships. *Bull. Amer. Meteor. Soc.,* **91,** 877–888.

Snellman, L. W., 1982: Impact of AFOS on operational forecasting. *Proc. Ninth Conf. on Weather Forecasting and Analysis,* Seattle, WA, Amer. Meteor. Soc., 13–16.

Stewart, A. E., 2009: Minding the weather: The measurement of weather salience. *Bull. Amer. Meteor. Soc.,* **90,** 1833–1841.

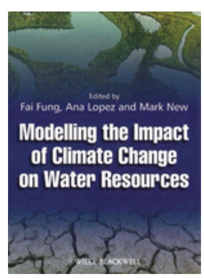
U.S. House of Representatives, 2006: A failure of initiative. U.S. House of Representatives Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina Final Rep., 520 pp. [Available online at www.gpoaccess.gov/katrinareport/fullreport.pdf.]

White, S. A., 2004: Introduction to BPMN. Object Management Group Rep., 11 pp. [Available online at www.omg.org/bpmn/Documents/Introduction_to_BPMN.pdf.]

MODELLING THE IMPACT OF CLIMATE CHANGE ON WATER RESOURCES

Fai Fung, Ana Lopez, and Mark New, Eds., 2010, 200 pp., $129.95, hardbound, Wiley-Blackwell, ISBN 978-1-4051-9671-0

A brief introduction presents the major themes discussed in this book and an overview of its organization. The chapter topics follow the typical steps performed in a study of the impact of climate change on water resources. The book provides an overview of the current state of the science and practice at a time when climate change is an active area of research and water managers are often unsure of how to use the uncertain climate projection information. The importance of the topic is evidenced by efforts by the Water Research Foundation to fund practical research for applying climate change information and by the Water Utilities Climate Alliance to identify additional research needs and data required by water managers.



The second chapter, "Weather and Climate," begins by discussing the differences between weather and climate, but then focuses the discussion on climate modeling. A simple energy balance model is contrasted with Global Climate Models (GCMs) to demonstrate that even a simple model can be effective in revealing some aspects of climate change. The reader is given a good introduction to climate modeling, including basic constructs, the need for parameterizations to capture small-scale processes, (e.g., cloud formation), difficulties in evaluating model outputs, sources of model uncertainty, and model limitations. The chapter touches on the important issues of concern to hydrologists, but some additional discussion of what information the models are not capable of providing might give hydrologists insight to avoid inappropriate uses of model outputs. A brief discussion is included of the possible advances in climate modeling over the next few years. More specific information about differences between the GCMs used in the Coupled Model Intercomparison Project (CMIP) 3 and the CMIP5 would be of interest to the reader, along with how this might impact their utility for impact analysis.

Chapter 3, "Regional Climate Downscaling," provides some historical perspective for downscaling and then presents an overview of downscaling approaches used today. The chapter includes less discussion of dynamic downscaling than statistical downscaling approaches; however, weather classification schemes, transfer functions, and weather generators are presented with sufficient detail. An extensive set of references is included for readers interested in more detail. The chapter provides a nice summary of downscaling intercomparison studies and makes the point that GCM boundary conditions are the main source of uncertainty affecting downscaling. The section on uncertainty discusses methods used and difficulties in estimating probability distributions of climate parameters based on ensemble experiments accounting for emission scenarios, climate model structure and parameterizations, initial conditions, and downscaling. The reader is left with the sense that there is more promise in improving estimates of the uncertainty than in reducing the uncertainty. A section on translating theory into practice presents three ways downscaling information is used to support adaptation planning: detecting hydrologic change, assessing impacts, and evaluating adaptation alternatives. The presentation includes a comprehensive summary of the work to date and points out that there are limited examples where downscaling has been an integral part of an adaptation evaluation exercise. The chapter concludes with an interesting discussion of the usefulness of climate scenarios, and stresses the importance of robust adaptation planning, particularly in regions where the uncertainty is large and there is no real consensus among climate models (e.g., sign of precipitation change or rate of warming).

Chapter 4, "Water for People: Climate Change and Water Availability," describes the traditional water supply planning process and presents an approach for planning to account for the impact of climate change. It begins with a discussion of the types of hydrologic models that can be used to estimate available water, and issues to be considered when selecting a hydrologic model. The discussion shifts to water supply systems and how the amount of deployable water can be computed from the supply–demand balance. A section on water demand identifies the direct and indirect climate change impacts on demand and provides some suggestions for estimating future demands. Water resource systems models are introduced as a powerful way to analyze the water supply–demand balance, as well as a useful tool to evaluate adaptation alternatives. The chapter ends with a philosophical discussion of a scenario-adaptation planning approach that provides a comprehensive analysis of alternatives across a range of climate scenarios to enable water planners to assess risks. It emphasizes the importance of selecting a balanced portfolio of alternatives that will provide flexibility and robustness in an uncertain climate future.

The discussion of adaptation planning continues in chapter 5, "Emerging Approaches to Climate Risk Management." The chapter emphasizes the need to move away from planning approaches that rely on known probability distributions of future streamflow. It reiterates earlier discussion that one approach is to insure that water supply systems can deal with variability in the current climate first, and then to identify vulnerabilities to a wide range of climate change scenarios. It is recommended that adaptation planning consider "low regret" options to insure that future options are not eliminated, and that plans should include alternative option pathways that can be triggered based on monitoring of climate parameters.

The final chapter presents three case studies of approaches to analyzing the impacts of climate change on water resources. The studies are taken from different countries and exemplify a range of complexity in approach. They demonstrate practical approaches to climate impact analysis and provide concrete examples for the reader who is new to the field.

Although the book is composed of contributions from several authors, it is well written and an easy read. At times there is overlap between topics discussed in different chapters, but that overlap is not excessive. Some of the figures presented in black-and-white could be enhanced through the use of color; however, it can be inconvenient to refer to the center section of the book where the color plates are found.

Overall, the book is highly recommended. It provides an excellent summary of the current state of the

NEW PUBLICATIONS

DROUGHT: PAST PROBLEMS AND FUTURE SCENARIOS

J. Sheffield and E. F. Wood, 2011, 248 pp., $84.95, hardbound, Routledge, ISBN 978-1-84971-082-4

The aim of this book is to review the historical occurrence of global drought and assess likely potential changes over the twenty-first century under climate change. It includes discussion of the environmental factors that act to force, prolong, and dissipate drought. It explores the developing field of drought monitoring and seasonal forecasting and describes how they are vital for identifying emerging droughts and for providing timely warnings to help reduce the impacts. It also provides a broad overview of large-scale drought and places it in the context of climate variability and change.

RENAISSANCE METEOROLOGY: POMPONAZZI TO DESCARTES

C. Martin, 2011, 224 pp., $50.00, hardbound, Johns Hopkins University Press, ISBN 978-1-4214-0187-4

This title looks at how Renaissance scientists analyzed and interpreted rain, wind, and other natural phenomena and how such events impacted the great thinkers of the scientific revolution. It argues that because meteorology involved conjecture and observation and forced attention to material and efficient causation, it paralleled developments in the natural philosophies of Descartes and other key figures of the scientific revolution. The book also explores how natural philosophers of the time debated the meanings, causes, and purposes of natural disasters and other weather phenomena.

INTRODUCTION TO MODERN CLIMATE CHANGE

A. E. Dessler, 2012, 238 pp., $110.00, hardbound, Cambridge University Press, ISBN 978-1-107-00189-3

The goal of this textbook is to prepare students to engage in the public policy debate on the issue of global climate change. It is divided into two separate sections: The first half is focused on the science, including evidence that the Earth is warming and a basic description of climate physics. This section also covers the concepts of radiative forcing, feedbacks, and the carbon cycle. The second half of the book goes beyond the science to address economics and policy, including a short history on the politics of climate science.

science and practice for water managers as well as for scientists who are new to the field. It provides water managers with suggestions about how to incorporate climate projection information into decision making, and realistic expectations about how the science will advance. A useful list of references is provided at the end of each chapter for the reader who wants additional information.

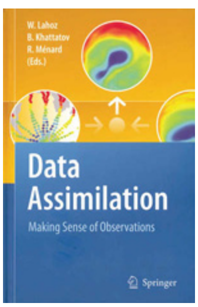
—Gerald N. Day

Gerald N. Day is director of water management and forecasting at Riverside Technology, inc.

DATA ASSIMILATION: MAKING SENSE OF OBSERVATIONS

William Lahoz, Boris Khattatov, and Richard Menard, Eds., 2010, 746 pp., $169.00, hardbound, Springer, ISBN 978-3-540-74702-4

Data Assimilation, edited by Lahoz, Khattatov, and Menard, is a collection of 25 review and research articles in a 700-page volume. The subtitle, *Making Sense of Observations*, is too modest, as the contributions discuss a very broad range of topics, including all aspects of atmospheric data assimilation science as well as applications beyond the Earth's atmosphere.



The book is divided into six sections and includes a detailed index and a list of acronyms. The first section, "Theory," comprises more than a third of the volume and presents a comprehensive overview of the data assimilation problem, followed by a rigorous description of variational data assimilation techniques and a review of some recent developments in ensemble Kalman filters. The section also contains several clear and detailed articles that focus on extending basic assimilation algorithms to situations in which both the forecast model and the observations have systematic errors. Most of the other articles in the first section—for instance one on evaluating assimilation algorithms—include some coordinated discussion on dealing with systematic error. I would recommend the first section to students of data assimilation, modelers, or observational experts who want to understand modern approaches for dealing with less than perfect models and observations.

The remaining sections of the volume are generally more descriptive and less mathematically rigorous than the first. The sections include descriptions of present and future observations focusing on the troposphere and stratosphere; an overview of atmospheric dynamics and numerical prediction models; a

SPATIOTEMPORAL DATA ANALYSIS

G. Eshel, 2012, 317 pp., $85.00, hardbound, Princeton University Press, ISBN 978-0-691-12891-7

This book introduces advanced undergraduate students, graduate students, and researchers to the statistical and algebraic methods used to analyze spatiotemporal data in a range of fields, including climate science, geophysics, ecology, and astrophysics. It begins with a primer on linear algebra, providing readers with the mathematical foundations needed for data analysis. It then explains the theory and methods for analyzing spatiotemporal data, from the basics to the most advanced applications. It features numerous real-world examples as well as sample homework exercises and suggested exams.

CLIMATE ADAPTATION AND FLOOD RISK IN COASTAL CITIES

J. Aerts et al., Eds., 2011, 332 pp., $84.95, hardbound, Routledge, ISBN 978-1-84971-346-7

This book presents climate adaptation and flood risk problems and solutions in coastal cities, including an independent investigation of adaptation paths and problems in Rotterdam, New York, and Jakarta. While the main focus is on coastal flooding, it also explores how cities are affected by climate change in other ways. The authors examine questions such as: Are current city plans climate-proof or do we need to fine-tune our ongoing investments? Can we develop a flood-proof subway system? And, can we develop new infrastructure in such a way that it serves flood protection, housing, and natural values?

CAMILLE, 1969: HISTORIES OF A HURRICANE

M. M. Smith, 2011, 90 pp., $24.95, hardbound, University of Georgia Press, ISBN 978-0-8203-3722-7

This title offers three distinct histories of the Hurricane Camille's impact in southern Mississippi. In the first essay, the author examines the sensory experience and impact of the hurricane. The second essay explains the way key federal officials linked the question of hurricane relief to the desegregation of Mississippi's public schools. The book concludes by considering the political economy of short- and long-term disaster recovery, returning to issues of race and class. Throughout these essays are lessons about how we might learn from the past in planning for recovery from natural disasters in the future.

review of atmospheric chemistry along with descriptions of data assimilation applications for constituent estimation and prediction; example assimilation applications for the land-surface, ocean, ionosphere, and Martian atmosphere; and applications of assimilation to climate change and observing system design. As a data assimilation scientist who works on many applications in geophysics, I found a number of these contributions to provide valuable overviews of the assimilation challenges faced by my collaborators. For example, the article on assimilation in the ionosphere presented the clearest introduction to this problem that I have read and helped to clear up several misconceptions I still had despite having provided assimilation tools for this problem for years.

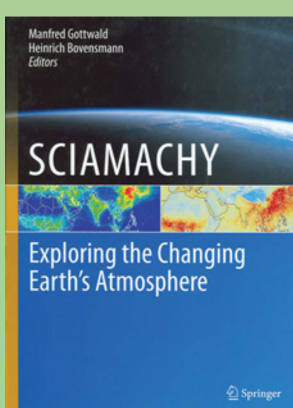
It is clearly impossible to present a complete description of the burgeoning science of data assimilation plus models, observations, and diverse applications in a single volume. Many contributions focus more on topics related to the operational numerical weather prediction activities at the European Centre for Medium-Range Weather Forecasts (ECMWF). A fairly detailed understanding of most aspects of the ECMWF global analysis system as it existed in 2009 could be gleaned from the volume, with somewhat less information about activities at the UK Meteorological Office and relatively little about those at NCEP or smaller operational centers. As a result, there is more information presented about the four-dimensional variational algorithms used at ECMWF than there is about ensemble Kalman filters

BIBLIOPHILIA

2011 ASLI'S CHOICE AWARD WINNERS

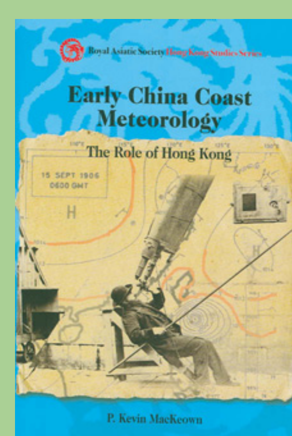
At January's AMS Annual Meeting in New Orleans, Atmospheric Science Librarians International (ASLI) announced the 2011 ASLI's Choice winners for the best books in the fields of meteorology, climatology, and atmospheric sciences.

This year, the ASLI's Choice committee selected a winner and honorable mentions in the categories of science and history. Selections were based on nine criteria: uniqueness, comprehensiveness, usefulness, quality, authoritativeness, organization, illustrations/diagrams, competition, and references.



The winning book in the science category was *SCIAMACHY: Exploring the Changing Earth's Atmosphere*, edited by Manfred Gottwald and Heinrich Bovensmann, published by Springer. ASLI noted the book provided a "comprehensive summary of the milestone SCIAMACHY mission from its initial conception to most recent results."

There were two honorable mentions in the science category: *The Global Cryosphere: Past, Present and Future*, by Roger G. Barry and Thian Yew Gan, published by Cambridge University Press, awarded for "the depth and breadth of its coverage of the major aspects of the cryosphere"; and *Physics and Chemistry of Clouds*, by Dennis Lamb and Johannes Verlinde, published by Cambridge University Press, for "its data-rich, yet readable exploration of clouds across a range of scales."



In the history category, the winner was *Early China Coast Meteorology: The Role of Hong Kong*, by P. Kevin MacKeown, published by Hong Kong University Press, which ASLI lauded for "its account of the scientists and science that comprise the history and accomplishments of the Hong Kong Observatory."

Honorable mention in the history category went to *The Warming Papers: The Scientific Foundation for the Climate Change Forecast*, edited by David Archer and Ray Pierrehumbert, published by Wiley-Blackwell, awarded "for a compendium of the key scientific papers that undergird the global warming forecast."

ASLI is a professional organization devoted to communicating and disseminating information among libraries and educational institutions involved in atmospheric science research and scholarship. ASLI is now seeking nominations for the 2012 ASLI's Choice awards; the deadline for nominations is November 1. For more information, go to http://aslionline.org/wp/asli-choice/.

ASLI congratulates all of the 2011 winners!

or other assimilation techniques. For instance, there is no discussion of the operational ensemble system at the Meteorological Service of Canada for comparison with the variational systems.

While reading *Data Assimilation*, I was led to consider what role a bound collection of contributions can play in a world where communication of science is increasingly done rapidly online. My copy of *Data Assimilation* is going to have a readily accessible place on my office bookshelf, and I expect to regularly reference some sections, particularly those on dealing with systematic errors and some of the nonatmospheric applications. However, some of the contributions are already showing their age. There are web references included in the text that are no long current, and the year of the latest publications referenced in some sections is 2009. For rapidly evolving fields like constituent data assimilation I expect that the volume will lose its relevance in a few years; however, the sections on fundamental assimilation algorithms should age much better.

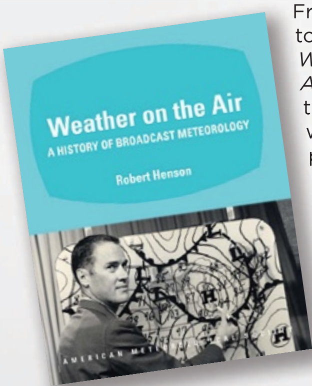
There are several audiences that would find *Data Assimilation* particularly useful. It would be challenging to use the volume as the principal text for a graduate-level data assimilation class due to a lack of exercises and limited background on the evolution of assimilation methods. However, I think it could be used effectively in conjunction with existing data assimilation textbooks to give students a broader view of opportunities and challenges in data assimilation science. The volume would also be quite helpful as an introduction to geophysical applications of assimilation for students or researchers with training in the technical aspects of state estimation but only a limited background in geoscience. I expect my copy to be in demand with future postdocs who have degrees from applied mathematics or statistics programs but are anxious to apply their skills to geophysical applications.

—Jeffrey Anderson

Jeffrey Anderson is a scientist in the Data Assimilation Research Section in the Institute for Mathematics Applied to Geosciences at the National Center for Atmospheric Research, where he leads the development of the Data Assimilation Research Testbed community ensemble assimilation facility.

HISTORY

Weather on the Air:
A History of Broadcast Meteorology
ROBERT HENSON



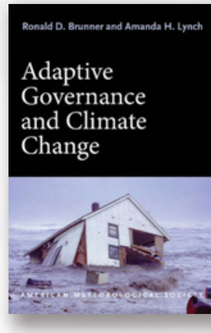
From low humor to high drama, *Weather on the Air* documents the evolution of weathercasts—the people, technology, science, and show business that combine to deliver the weather to the public each day. An invaluable tool for students of broadcast meteorology, this book will entertain anyone fascinated by the public face of weather. Includes over 100 photographs!

©2010, HARDCOVER, 264 PAGES, ISBN 978-1-878220-98-1 , AMS CODE: WOTA

LIST $35 MEMBER $25

CLIMATE CHANGE

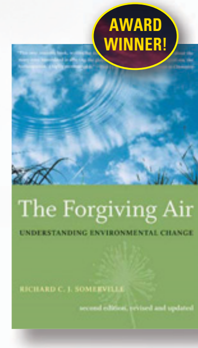
ASK ABOUT THE HISTORIC ARCHIVE OF CALLENDAR'S PAPERS AVAILABLE ON DVD.



Adaptive Governance and Climate Change
RONALD D. BRUNNER AND AMANDA H. LYNCH

©2010, PAPERBACK, 424 PAGES, ISBN 978-1-878220-97-4, AMS CODE: AGCC

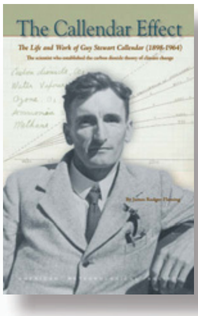
LIST $35 MEMBER $22



The Forgiving Air: Understanding Environmental Change, 2nd ed.
RICHARD C. J. SOMERVILLE

©2008, PAPERBACK, 224 PAGES, ISBN 978-1-878220-85-1, AMS CODE: TFA

LIST $22 MEMBER $16

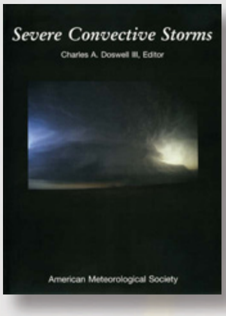


The Callendar Effect: The Life and Work of Guy Stewart Callendar (1898–1964)
JAMES RODGER FLEMING

© 2007, HARDCOVER, 176 PAGES HM, ISBN 978-1-878220-76-9, AMS CODE: CLDR

LIST $34.95 MEMBER $24.95

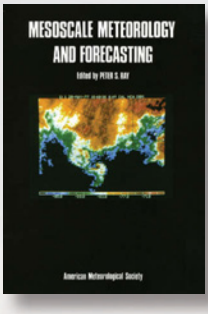
CONVECTIVE PROCESSES



Severe Convective Storms
EDITED BY CHARLES A. DOSWELL III

© 2001, HARDCOVER, 570 PAGES, MM VOL. 28, NO. 50, ISBN 978-1-878220-41-7, AMS CODE: MM50

LIST $110 MEMBER $90
STUDENT MEM. $75

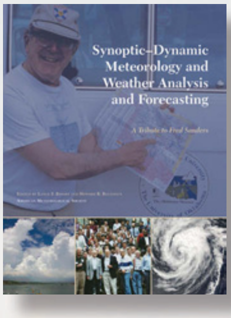


Mesoscale Meteorology and Forecasting
EDITED BY PETER S. RAY

© 1986, HARDCOVER, 793 PAGES, ISBN 978-0-933876-66-8, AMS CODE: MESOMET

LIST $76.25 MEMBER $66.25
STUDENT MEM. $56.25

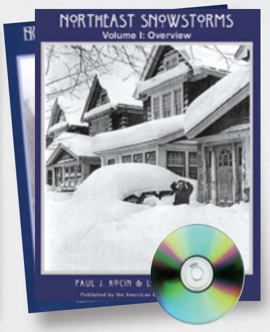
MIDLATITUDE WEATHER SYSTEMS



Synoptic–Dynamic Meteorology and Weather Analysis and Forecasting: A Tribute to Fred Sanders
EDITED BY LANCE F. BOSART AND HOWARD B. BLUESTEIN

© 2008, HARDCOVER, 440 PAGES, MM VOL. 33, NO. 55, ISBN 978-1-878220-84-4, AMS CODE: MM55

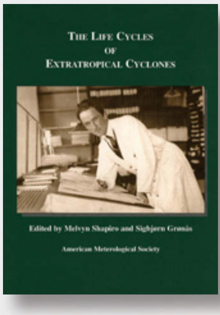
LIST $120 MEMBER $80
STUDENT MEM. $60



Northeast Snowstorms (Volume I: Overview, Volume II: The Cases)
PAUL J. KOCIN AND LOUIS W. UCCELLINI

© 2004, TWO HARDCOVER VOLS, 818 PAGES, MM VOL. 32, NO. 54, ISBN 978-1-878220-64-6, AMS CODE: MM54

LIST $100 MEMBER $80
STUDENT MEM. $60



The Life Cycles of Extratropical Cyclones
EDITED BY MELVYN A. SHAPIRO AND SIGBJØRN GRØNÅS

© 1999, HARDCOVER, 359 PAGES, ISBN 978-1-878220-35-6, AMS CODE: LEC

LIST $75 MEMBER $55

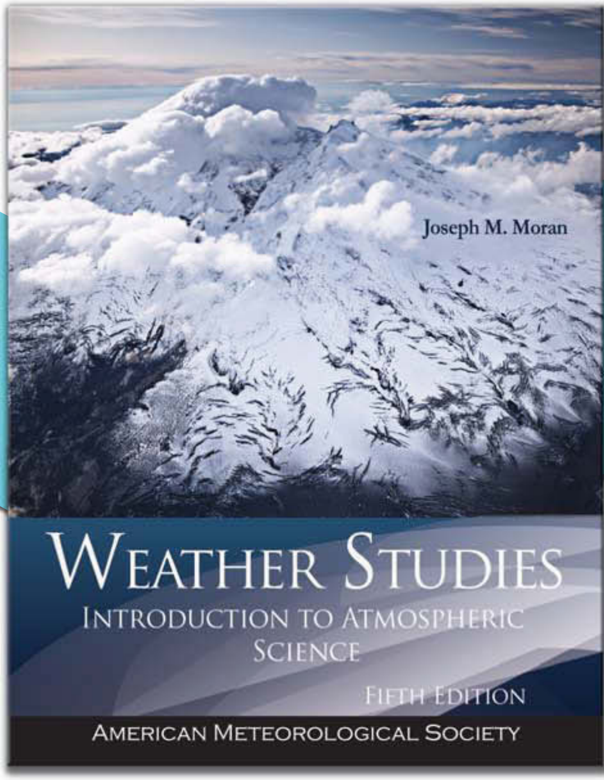
MM = METEOROLOGICAL MONOGRAPH SERIES
HM = HISTORICAL MONOGRAPH SERIES

Booksellers and wholesale distributors, to place an order please contact The University of Chicago Press: 1-800-621-2736 (US & Canada) 773-702-7000 (all others) custserv@press.uchicago.edu

AMS MEMBERS AND STUDENT MEMBERS GET DEEP DISCOUNTS!

SUMMER 2012

For more Information: *http://www.ametsoc.org/amsedu/online/info/*



To Request a Complimentary Review Copy
http://www.ametsoc.org/onlinewxcfm/weatherstudiesrequest.cfm
onlinewx@ametsoc.org
(800) 824-0405

AMS WEATHER STUDIES
5th Edition

Weather Studies places students in a dynamic, and motivational learning environment using real-world environmental data. Key meteorological concepts such as temperature, pressure, and stability are introduced. The 5th edition textbook features discussions on atmospheric rivers, the record-breaking 2011 tornado season, and hurricane-related extreme flooding events. A fresh, new look includes the addition of QR codes enabling access to animations and extra imagery. Proceeds support AMS K-12 Professional Development.

COMING SOON

ANNUAL REPORT FOR 2011 NOW AVAILABLE

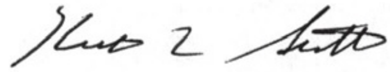
The 2011 Annual Report, which covers the highlights of the Society's various programs over the course of the prior calendar year, was recently posted on the AMS website. It will be linked to prominently from the home page for the next few months, but will always be available—along with the reports from prior years—on the pages that provide the documentation on the Society's administration.

It is hard to characterize 2011 as anything but very successful in terms of the various programs and initiatives of the Society. The Annual Meeting always seems to set a tone for the coming months as it kicks off the year in January. The 2011 Annual Meeting in Seattle was well attended, and its theme of communications resonated with the community throughout the various components of the meeting. Building on many ideas introduced at the Seattle meeting, and applied to a theme of technological advances in our community, AMS President Jon Malay worked with the organizing committee over the course of last year to prepare for the 2012 Annual Meeting that would kick off the current year just as successfully.

The AMS journals completed the recovery from the prior year's data loss with less impact on the production times than had been feared (though we deeply regret the impact of the data loss on those authors whose papers were directly affected), and ended the year with strong submissions. Despite the economic uncertainties, the important meetings throughout the year organized by boards and committees within the STAC, Professional Affairs, and Weather and Climate Enterprise commissions were well attended and programmatically successful. Efforts to expand the breadth of the community served by the AMS were realized with the creation of several new boards and committees that reach into sciences that intersect with the atmospheric sciences. The Society's certification programs, educational initiatives, and input to national policy discussions were also vibrant. A review of the highlights summarized in the 2011 Annual Report will show the Society to be focused on its mission and making great progress toward its goals and objectives through the efforts of more than 900 volunteers serving in the various boards and committees who are listed in the report. In addition, there are more than 1,000 dedicated volunteers who serve as journal manuscript reviewers who also help to carry out the work of the AMS.

The acquisition of the building next door to the longtime AMS Headquarters at 45 Beacon Street in Boston was reported in the 2010 Annual Report, but 2011 represented the year that the 44 Beacon Street property was integrated into the Headquarters operation. The relatively minor, but time-consuming, renovations required to bring the space into compliance with various fire and safety codes, as well as upgrading the physical systems without compromising the historical character of the building, ended up taking most of the year. As reconfiguration of staff started taking shape in late 2011, the economic value of this acquisition began being realized. The additional space allowed existing departments to reconfigure in ways that led to more efficient operations, and several staff positions that support the Society's publications operations, which had been located elsewhere, began the process of being consolidated at Headquarters. This consolidation of staff has already led to increased levels of support with decreased cost. It is projected that the savings from these efforts will soon reach a level close to the annual debt service on the building—meaning that what was already a prudent investment for the Society goes well beyond that.

I encourage you all to take a few minutes to peruse the 2011 Annual Report available on the AMS website. I am confident you will be proud of all that the Society accomplished last year on behalf of our community, and many of you will be surprised at the breadth of the initiatives that continue to serve not only our community, but society as a whole.



KEITH L. SEITTER, CCM
EXECUTIVE DIRECTOR

OBITUARIES

DAVID GRIMES
1951–2011

David Ian Francis Grimes, leader in African meteorology, died on 22 December 2011 at the age of 60 following the sudden onset of a rare neurological disorder, the sporadic form of Creutzfeldt-Jakob Disease.

David joined the Department of Meteorology at the University of Reading, United Kingdom, in 1990, from where he recently received his long-service award. David was renowned for the care that he showed to students, playing major roles in the administration of both undergraduate and masters' courses over many years. Students recall the warmth of David's welcomes on their arrival at Reading, as he was often the first member of staff that they met. David was a skilled and dedicated teacher, often illustrating his lectures with his own, sometimes very amusing, cartoons. He also contributed to and led many field trips with his characteristic energy and humor.

David trained as a physicist, and after spells at the University of Leicester and the Open University, he moved to Reading to perform research on the use of satellite data to monitor rainfall over the whole of Africa. His scientific drive was accompanied by an equally strong desire to insure that the science that he did was of clear benefit to those whose lives are reliant on what the weather brings. He joined the Department's TAMSAT (Tropical Applications of Meteorology using SATellite data and ground-based observations) research group, and took over its leadership in the mid-1990s. TAMSAT produces data that allow African meteorologists to monitor the progress of their rainy seasons and to give early warning of floods and droughts. With more than 20 years of satellite data now available, the same data are being used to understand African climate change and climate variability.

The longevity of TAMSAT as a force in African meteorology comes down to an underlying simplicity of method that has proven itself time and again to be more robust than apparently more sophisticated methods. David authored or coauthored 27 papers on various aspects of African rainfall, exploring novel approaches to exploiting data that led to links with hydrologists, statisticians, and agricultural scientists, in Reading and beyond, which made TAMSAT's work of even more relevance to real-world problems. David was also passionate about training and inspiring new generations of African scientists, which he achieved either via many training schools in Africa or by attracting African scientists to Reading. He was also often frustrated by the bureaucratic barriers that prevented African students from coming to Reading to train, and showed no fear in challenging such decisions.

David Grimes

In 2010, TAMSAT received the "IBM Award for Meteorological Innovation that Matters," which is administered by the Royal Meteorological Society. In the citation for that award it states that TAMSAT

> "continues to deliver massive benefits to Africa in terms of essential rainfall predictions, through the use of satellites. Operationally, the rainfall products generated by TAMSAT are used extensively by African weather services, providing a unique and essential

IN MEMORIAM

SCOTT FORREST ARCHER
1954–2011

source of data. This technology providing precipitation information is of such importance in developing regions, that it merits this recognition. From its inception, TAMSAT have shown how even the early generations of satellite technology can be harnessed quantitatively to provide vital rainfall information over a wide region."

David will be greatly missed and remembered with great affection, not only by his friends, colleagues, and students in the Department of Meteorology, but also by meteorologists all over Africa and beyond who David has influenced via either his teaching or his research collaborations.

— Keith Shine

GOING GREEN

Introducing the AMS Committee on Environmental Responsibility

If AMS had a "team color," you might imagine that it's blue, given the Society's blue logo and its scientific focus on the sky and seas. But AMS has been going green. Over the past couple of years, the Society has been focusing on the environmental impact of its activities and trying to have a gentler footprint. The professional staff, elected leadership, and volunteer members are all involved with this green initiative, coordinated by the newly established Committee on Environmental Responsibility. Over the next several months, the "45 Beacon" section of *BAMS* will feature short stories on some of the committee's activities. This month, we describe the committee's genesis, a "grassroots" movement, appropriately enough.

For years, AMS member Eugene Cordero, professor of meteorology and climate science at San Jose State University and coauthor (with Laura Stec) of the book *Cool Cuisine: Taking the Bite out of Global Warming*, had been concerned about food service at AMS Annual Meetings. From the amount of wasted food, to the lack of recycling bins for disposable food containers, to the choice of menu items, Eugene saw opportunities for more environmentally responsible choices and raised the issue with the AMS Council. In April 2007, the AMS Executive Committee established an Ad Hoc Committee on Green Meetings, chaired by Eugene, to develop recommendations for environmentally responsible practices for AMS meetings, including food service. The result was the AMS Green Conference Guidelines, adopted by the Council in September 2007 and implemented at the 2008 Annual Meeting in New Orleans. We'll report on the specifics of these guidelines next month.

To build on the Ad Hoc Committee's work on green meetings, the Executive Committee established the Committee on Environmental Responsibility, as a standing committee of the Executive Council, in April 2009. That committee's responsibilities are "[t]o seek to improve the environmental responsibility of the Society's operations, to strive to make the Society a leading example of effective environmental stewardship, and to serve as a source of information for others with similar aspirations." Dian Seidel of the NOAA Air Resources Laboratory currently chairs the committee of 14 members, including two student members. You can visit the committee website for terms of reference, membership roster, and work plan at www.ametsoc.org/committeepges/envres/index.html.

In the coming months, look for more stories in "45 Beacon" on enhancing energy efficiency in AMS office buildings, environmentally responsible investment strategies for the AMS portfolio, greening AMS publications, community outreach at AMS Annual Meetings, and more.

CERTIFIED CONSULTING METEOROLOGISTS (CCM)

The following individuals were recently granted the Certified Consulting Meteorologist (CCM) designation. For more information on the AMS CCM program, go to www.ametsoc.org/amscert/index.html#ccm.

679	**Lance Steele**	**2012**
680	**Richard Walker Jr.**	**2012**
681	**Stephen Mark Leidner**	**2012**
682	**Ronald Lowther**	**2012**
683	**Daniel Lennartson**	**2012**

David C. Curtis has been appointed to a three-year term on the California Department of Water Resources (DWR)'s Climate Change Technical Advisory Group (CCTAG). Curtis joins experts from both the public and private sectors and academia as a panelist responsible for advising DWR on the scientific aspects of climate change, its impacts on water resources, the use and creation of planning approaches and analytical tools, and the development of adaptation responses for California's water sector.

For the past 40 years, Curtis has worked designing, developing, and implementing award-winning innovations in more than 50 automated river- and flood-monitoring systems across the United States and in 18 countries abroad. His most recent work involves applying new climate and weather information technologies such as radar-rainfall and satellite estimates to flood warning, hydrologic analysis, and modeling. He has led several state-of-the-art efforts utilizing gauge-adjusted radar rainfall estimates to develop improved design storms that potentially impact hydrologic standards throughout the United States.

Curtis is vice president of Northern California of WEST Consultants, as well as the current president of the National Hydrologic Warning Council.

WEST Consultants is a water resources engineering firm with more than 60 employees in seven offices in Oregon, Washington, California, and Arizona.

MINUTES

MEETING OF THE COUNCIL

22–23 September 2011, Boston, Massachusetts

Participants—President Jon Malay, President-Elect Louis Uccellini, Past-President Peggy LeMone, Executive Director Keith Seitter, and Secretary-Treasurer Richard Rosen. Councilors: Ken Carey, Anne Douglass, Mike Hardesty, Jill Hasling, Peter Lamb, Rebecca Morss, Pat Phoebus, Bill Read, John Schaake, Richard Spinrad, Joe Witte, and Xubin Zeng. Commissioners: David Jorgensen (Publications), Jay Trobec (Professional Affairs), Mary Cairns (STAC), Gene Takle (Education and Human Resources), Len Pietrafesa (Weather and Climate Enterprise), and Julie Winkler (Planning). Past-President Tom Karl, and Councilors Tom Bogdan, Lee Branscome, and Ahsha Tribble were absent. AMS Staff: Joyce Annese, Stephanie Armstrong, James Brey, Melissa Fernau, Claudia Gorski, Ken Heideman, Paul Higgins, William Hooke, Barry Mohan, Anne McDonough, Gary Rasmussen, and Melissa Weston. Annese and Seitter served as recorders.

[The numbering of the following sections follows that in the agenda, but the sections are listed in the order they were addressed at the meeting.]

0.0 AGENDA. President Malay called the meeting to order at 8:30 A.M. on Thursday, 22 September 2011, and welcomed all. The roll was called, and Secretary-Treasurer Rosen announced a quorum of voting members was present. President Malay reviewed the agenda.

1.3 COUNCIL MINUTES. The Council reviewed and approved the minutes from its meeting in Seattle, WA, 23 January 2011, and approved the minutes of its conference call on 3 January 2011.

1.5 COUNCIL MAIL BALLOTS. All Council e-mail ballots not previously approved unanimously were formally approved, and ballots that were "provisionally approved" were formally approved.

2.1 SCIENTIFIC AND TECHNOLOGICAL ACTIVITIES COMMISSION. Commissioner Cairns presented her report. The Council approved forming a Board on Environment and Health (BEH) and asked final terms of reference be provided in January. The Council approved converting the Ad Hoc Committee on Data Stewardship under the Executive Committee (EC) to a Board on Data Stewardship within STAC, but with recommendations for initial membership of the Board and modifications to its terms of reference, which will be presented in January for final approval. The

Council also approved converting the IIPS Committee under the EC to a STAC Board on Environmental Information Processing Technologies (BEIPT). The terms of reference and membership for the Board were approved by the Council.

Commissioner Cairns requested and received Council approval for a named symposium in honor of Robert Duce for the 2013 Annual Meeting. She also reviewed other activities within the Commission, including recommendations for named symposia beyond 2013. Commissioner Cairns had concerns about a request for an international meeting given the state of the economy, and asked Council for their thoughts before the Radar Committee went through the work of putting together a formal proposal. The Council felt international outreach is important, especially with strong radar interests in Asia, and would be supportive of the proposal for a meeting in Japan in 2013.

The proposal for an AMS Statement on Social Sciences was reviewed, and the Council approved moving forward with the Statement while requesting that a more specific title be developed.

[The Council briefly recessed from 9:55 A.M. to 10:05 A.M.]

2.1 PUBLICATIONS COMMISSION. Commissioner Jorgensen commended the Publications Department for its efforts in implementing the new manuscript tracking system. He also reported on the reduction in color charges to authors, the plans to do an author survey, publication submissions, and appointments of new editors. It was suggested that the Board on Weather Analysis and Forecasting approach the Department of Defense to engage that portion of the operational forecasting community. The Council approved the appointment to three-year terms ending in 2015 for David A. Kristovich, Chief Editor, *Journal of Applied Meteorology and Climatology*; Christa D. Peters-Lidard, Chief Editor, *Journal of Hydrometeorology*; and Paul M. Markowski, Chief Editor, *Weather Analysis and Forecasting*.

2.2.1 AN OPEN-ACCESS CHOICE FOR AUTHORS PUBLISHING IN AMS JOURNALS. Commissioner Jorgensen explained this option and the added fee for this service. The Council approved having the staff introduce an open-choice option for authors as soon as the details of pricing and implementation could be resolved.

2.2 PROFESSIONAL AFFAIRS COMMISSIONER. Commissioner Trobec summarized activities of the Commission over the past year and provided a brief review of the boards under his Commission, along with appointments of new members.

2.4 EDUCATION AND HUMAN RESOURCES COMMISSION. Commissioner Takle reviewed the activities of the Commission and provided reports from the boards within his Commission.

2.4.1 EDUCATION AND HUMAN RESOURCES COMMISSIONER. Commissioner Takle completes his three-year term in January. The EC presented two candidates to replace Commissioner Takle, and after discussion, the Council approved David A. Smith as the new Education and Human Resources Commissioner for a term ending January 2015. The Council commended Commissioner Takle for his service.

2.5 PLANNING COMMISSION. Commissioner Winkler reported on efforts within the Commission to review progress on recommendations coming from both the 2006 External Review Report and the 2007 AMS Strategic Goals document and associated implementation plans. Commissioner Winkler asked each commissioner to provide updates to their Strategic Goals Implementation Plan by 1 November. The Planning Commission will have a preliminary report in January for the Council.

Commissioner Winkler also presented a recommendation to consider a young professional for appointment to the Fifth Councilor position this year. Possible candidates for Fifth Councilor were discussed in preparation for a later agenda item on this appointment. The Council approved Wendy Abshire to a four-year term on the Commission ending January 2016.

2.6 WEATHER AND CLIMATE ENTERPRISE COMMISSION. Commissioner Pietrafesa presented his report, which included proposed changes to the Organizational Procedures for his Commission to codify current structure and practice. The Council approved the proposed changes, as well as the proposed new membership list for the Commission's Steering Committee. In response to a request for guidance about possible emeritus or legacy appointments to the Steering

Committee, the Council stated its preference for a rotation of members and that past members should not formally continue serving after their terms expire.

2.6.1 WEATHER AND CLIMATE ENTERPRISE FUTURE COMMISSIONER. President Malay reported the discussion by the EC about possible candidates for future commissioner and its recommendation that Mary Glackin serve as the new future commissioner. The Council approved the recommendation.

[The Council recessed for lunch from 12:25 P.M. to 1:15 P.M.]

3.1 AD HOC COMMITTEE ON STATEMENTS. Councilor Morss, chair of the Ad Hoc Committee on Statements, presented her report on dealing with statements approved prior to 2007. The Council commended the Committee for its efforts and accepted its recommendations as amended. The Council discussed the desirability of continuing to make out-of-force statements available on the AMS website, but in a manner that clearly identified them as no longer in force. The Council charged the Executive Director with implementing the report's recommendations.

3.3 STATEMENT ON FREEDOM OF SCIENTIFIC EXPRESSION. After discussion, the Council voted to approve the EC as the drafting committee for a revised Statement.

3.4 STATEMENT ON CLIMATE CHANGE. After a lengthy discussion led by Councilor Lamb, who is the Council representative to the drafting committee, the Council agreed to an approach toward a new draft of the statement that builds on the 2007 version of the statement. The Council thanked the drafting committee for its efforts to date and expressed its desire for the committee to continue working toward a draft that incorporates the Council's discussion.

3.5 STATUS OF STATEMENTS IN PROCESS. Executive Director Seitter reviewed the status of other Statements in progress.

4.1 STATUS OF 2011 BUDGET. Executive Director Seitter reviewed the status of the 2011 budget and projections for the remainder of the year.

[The Council briefly recessed from 3:30 P.M. to 3:45 P.M.]

4.2 2012 PROPOSED BUDGET. Executive Director Seitter reviewed the Society's performance versus budget for 2010 and the 2011 revised budget. He then proposed a budget for 2012, which was recommended for approval by the EC. After discussion on various aspects of the budget, the Council voted to accept the 2012 budget as proposed.

4.3 UNA REPORT. The Council was provided a history of the Society's financial reserves, including its unrestricted net assets, for the past 15 years.

4.4 BUDGET CREATION AND IMPLEMENTATION GUIDELINES. Executive Director Seitter presented the guidelines, which were approved by the Council in 2009 and are to be reviewed annually.

4.5 PAGE-CHARGE WAIVER COMMITTEE. Publications Director Heideman reported on the success of the page-charge waiver system. Councilors Morss and Hardesty complete their terms on the Waiver Committee in January, and the Council thanked them for their service. Councilors Zeng and Read volunteered to serve on this Committee, and Councilor Schaake agreed to continue his service.

5.1 AWARDS OVERSIGHT COMMITTEE REPORT. Past-President LeMone reviewed the process followed by the Committee. The Council considered the list of proposed awardees and citations, and it voted to approve all those proposed. The Council was provided an updated description for the Henry T. Harrison Award for Outstanding Contributions by a Consulting Meteorologist in advance of further discussion the next day.

5.2 AWARDS NOMINATIONS COMMITTEE REPORT. The report forwarded by Joe Friday was reviewed, and the Council expressed its appreciation for the efforts of the Committee. The Council concurred with the recommendation that the chair of the Committee serve as nonvoting ex officio on the Awards Oversight Committee to facilitate communication between the two committees.

5.3 PROPOSAL FOR NAMING A ROOM. Past-President LeMone discussed the proposal for naming a room at AMS Headquarters in honor of Joanne Simpson, in addition to those named in honor of Rossby, Brooks, and Spengler. The policy approved in

January calls for the Council to invite a small number of letters of support for consideration at its next meeting. Several councilors volunteered to secure the required letters.

5.4 POLICY, GUIDELINES, AND PROCEDURES FOR AWARDS. Past-President LeMone reviewed the changes to this document requested by STAC Commissioner Cairns. The majority of these changes are intended to clarify procedures for several of the awards, including the creation of separate categories and procedures for Society and Commission awards. The Council approved the proposed changes, and President Malay thanked LeMone and others for their efforts to date, recognizing that more work on the procedures will be needed over the next year.

5.5 WEXLER MEMORIAL LECTURE. Executive Director Seitter presented a proposal from the History Committee to reestablish the Wexler Memorial Lecture. The award was given only a few times after its creation in 1961, and a review of various options led to the decision that further discussion be held the following day.

6.0 PROPOSED AMS FELLOWS. In the absence of Past-President and Chair of the Fellows Committee Karl, President Malay presented the list of proposed new Fellows. Council discussed and approved the following candidates for Fellows:

Philip E. Ardanuy
Anthony J. Broccoli
Richard D. Clark
Timothy J. Dunkerton
Chris Elfring
Charles W. French
Richard Grumm
Fiona M. Horsfall
Christian D. Kummerow
Francois X. LeDimet
Zhengyu Liu
Donald R. MacGorman
Frank J. Misciasci
Paul Newman
Edward A. O'Lenic
Harry A. Otten
David Pace
Christa D. Peters-Lidard
Robert Pinkel
Gerald Potter
Mark Powell, CCM
William L. Read
David Robinson
Steven Root, CCM
Lynn K. (Nick) Shay
Roland B. Stull, CCM
Eugene S. Takle, CCM
H. Joe Witte
Marilyn M. Wolfson
Donald J. Wuebbles

President Malay reminded the Council that Cleveland Abbe Award winner Chris Elfring and Stommel Award winner Robert Pinkel were elevated to Fellow in conjunction with receiving these top AMS Awards. Councilors Read and Witte recused themselves from the discussion and vote.

[The Council adjourned for the day at 5:35 P.M. The meeting resumed at 8:00 A.M. on 23 September 2011 with the same voting and ex officio members present.]

7.0 HONORARY MEMBERS. The Council discussed and voted to approve Wilfried Brutsaert, J. Michael Wallace, and Yoshi K. Sasaki as 2012 Honorary Members.

5.1(CONTINUED) AWARDS OVERSIGHT COMMITTEE REPORT. Past-President LeMone continued the discussion from yesterday regarding the Henry T. Harrison Award for Outstanding Contributions by a Consulting Meteorologist, and the Council approved the terms of reference for this new award.

8.0 FELLOWS AND AWARDS NOMINATIONS COMMITTEES FOR 2012. The Council discussed and approved Eileen Shea and Jim Block as members of the Fellows Committee for three-year terms ending January 2015. The Council approved the appointment of Mike Gregg, John Dutton, and Dick Johnson as members of the Awards Nominations Committee for three-year terms ending 2015.

9.0 CONSTITUTION, BYLAWS, AND ORGANIZATIONAL PROCEDURES. Executive Director Seitter reviewed the process for revising the constitution, bylaws, and organizational procedures of the Society in preparation for the discussion of the following three items.

9.1 MEMBERSHIP CRITERIA CHANGES TO THE CONSTITUTION [ARTICLE III]. Executive Director Seitter reviewed the proposed constitutional changes for membership criteria that had been developed through extensive discussions over the past year. The Council approved the proposed language subject to review by AMS legal counsel, with the intention of approving in January the amendments prepared for member consideration and vote later in 2012. A related change to the bylaws will be prepared and submitted to each member of the Council at least 30 days in advance of the Council meeting in January to allow the Council to approve this amendment then.

9.2 ELECTION RULES CHANGES TO THE CONSTITUTION [ARTICLE VI]. Executive Director Seitter presented the proposed constitutional changes to allow additional flexibility in setting the structure of the Council ballot and to modify the date for closing the election. The Council approved the proposed language subject to review by AMS legal counsel, with the intention of approving in January the amendments prepared for member consideration and vote later in 2012.

9.3 PROFESSIONAL GUIDELINES CHANGES TO THE CONSTITUTION [ARTICLE XII]. Executive Director Seitter presented a minor change, proposed by the Planning Commission, to the professional guidelines of the constitution. The Council approved the proposed language subject to review by AMS legal counsel, with the intention of approving in January the amendments prepared for member consideration and vote later in 2012.

10.1 HISTORY COMMITTEE. President Malay briefed the Council on the report from the History Committee.

10.2 IIPS COMMITTEE. President Malay reviewed the report from the IIPS Committee and declared this the final report of the Committee, which now falls under STAC as the Environmental Information Processing Technologies Board. The Council expressed its appreciation to the Committee, especially cochairs Whittaker and Roberts and STAC Commissioner Cairns, for their hard work in the transition of this Committee.

10.3 LOCAL CHAPTER AFFAIRS COMMITTEE. President Malay reviewed the Local Chapter Affairs report and applauded all the efforts by the local chapters for the Society.

10.4 INVESTMENTS COMMITTEE. Executive Director Seitter and Controller Mohan provided information on the Society's investment portfolio.

10.5 ANNUAL MEETING OVERSIGHT COMMITTEE. President Malay reviewed the report of this Committee and expressed his appreciation for the work it has done.

10.6 DEVELOPMENT COMMITTEE. Executive Director Seitter briefly reviewed the plans being discussed in preparation for the 100th anniversary of the Society.

10.7 MEMBERSHIP COMMITTEE REPORT. Councilor Carey, chair of the Membership Committee, reviewed ongoing activities of the Committee, including working more closely with local chapters, increasing the participation of young professionals, and reaching out to the geography community.

10.8 ENVIRONMENTAL RESPONSIBILITY COMMITTEE. Executive Director Seitter presented the report of this Committee. President Malay stated he will become the EC's liaison to the Committee.

10.9 AD HOC ON DATA STEWARDSHIP COMMITTEE. Executive Director Seitter noted this will be the last report from this Committee given its transition to STAC as the Board on Data Stewardship.

11.0 FIFTH COUNCILOR. The Council discussed the recommendation from the Planning Commission to appoint a young professional as fifth councilor. The Council agreed on the need for input from younger members in the governance, but after considerable discussion the consensus of the Council was that there had been success in recent years in electing young professionals to the Council, and the Nominating Committee should continue to work toward including such individuals on the ballot. The Council agreed to consider candidates from the following areas: private sector, broadcasters, sustainability, or health. Councilors were asked to provide brief biographies of proposed candidates to the Executive Director by mid-October for further online discussion with the intention of creating a short list for consideration and selection. In addition, the Planning Commission was asked to consider more broadly the issue of engaging early-career individuals in the work of the Society.

12.0 21ST CENTURY CAMPAIGN. Informational reports were provided to the Council on 21st Century Campaign activities, as well as scholarships, fellowships, and other student programs made possible by external support.

13.1 MEETINGS. Director of Meetings Gorski reported on specialty meetings of the past year and those currently planned, as well as locations for future annual meetings beyond 2014.

13.2 2012 ANNUAL MEETING. President Malay reviewed plans for the Annual Meeting in New Orleans in January.

13.3 2013 ANNUAL MEETING. President-Elect Uccellini outlined the planning for the Annual Meeting in Austin in January 2013. The Council expressed its pleasure with the plans for both meetings.

[The Council briefly recessed from 10:30 A.M. to 10:40 A.M.]

14.1 PUBLICATIONS. Director of Publications Heideman reviewed his report on publication activities at AMS Headquarters, including the books program.

14.2 K–13 EDUCATIONAL INITIATIVES. Director of Education Program Brey described the activities of the program, including new grant support, programs for minority-serving institutions, and the release of the third edition of the *AMS Ocean Studies* textbook.

14.3 REPORT ON MEMBERSHIP. Executive Director Seitter and Director of Membership Farley presented the report on membership.

14.4 POLICY PROGRAM. Policy Program Director Hooke and Assistant Director and Senior Policy Fellow Higgins reviewed the activities of the Policy Program.

14.5 SCIENCE, SERVICE, AND SOCIETY. Executive Director Seitter reported on efforts to disseminate statements of the Society, as well as activities carried out under the Framework for Government Interactions.

14.6 AMS/SIGMA XI LECTURER. President Malay reported that Rick Anthes will serve as AMS/Sigma Xi Lecturer for 2012–13 and that Franco Einaudi is enjoying his term as Lecturer for 2011–12.

14.7 BOSTON AND DC OFFICE SPACE. Executive Director Seitter updated the Council on the status of the building at 44 Beacon Street and the plan that it be occupied in the next month. The D.C. staff is planning a move to new space in the AAAS building sometime around March 2012.

15.0 AMS AFFILIATIONS WITH OTHER ORGANIZATIONS. Executive Director Seitter reviewed the list of AMS affiliations with other organizations.

5.5(CONTINUED) WEXLER MEMORIAL LECTURE. Discussion resumed on whether or not to reestablish this dormant award. STAC Commissioner Cairns, with assistance from the AOC and possibly the new Environmental Information Processing Technologies Board, will work on terms of reference that include interaction with the History Committee and the Weather and Climate Enterprise Commission for possible approval at the January meeting so that the Wexler Lectureship can be announced at appropriate venues in New Orleans.

[The Council adjourned at 12:20 P.M.]

LIVING ON THE REAL WORLD

[Editor's Note: The following post is excerpted from William Hooke's blog, Living on the Real World (www.livingontherealworld.org/). Hooke is director of the AMS Policy Program.]

When It Comes to Tornadoes and Other Hazards. . . *[Originally posted on 6 March 2012]*
What kind of world do we want?

The Declaration of Independence pretty much spells it out, doesn't it . . . at least for Americans?

Well worth a (re)read in its entirety. [But you already knew that.] For present purposes, let's focus on this one piece:

". . .We hold these truths to be self-evident, that all men are created equal, that they are endowed by their Creator with certain unalienable Rights, that among these are Life, Liberty and the pursuit of Happiness. That to secure these rights, Governments are instituted among Men, deriving their just powers from the consent of the governed. . . ."

We claim our right to life, liberty, and the pursuit of happiness—even in the face of a world of hazardous extremes. And we expect our governments to provide no less.

Given that extremes of nature (not just tornadoes, but also hurricanes, cycles of flood and drought, winter storms, earthquakes volcanic eruptions, and so much more) are recurrent, inescapable realities, what do we realistically seek? Here are some notional suggestions. The hope is they'll inspire you to develop your improved or perhaps entirely different, better list.

The right to life *in the face of hazards?* This might translate to:

A warning. For weather extremes, since forecasts show skill, this would include forecasts of major hazards such as floods, drought, winter storms, hurricanes, hail storms, lightning . . . and those tornadoes. Watches for places and times of special risk several hours ahead of time. Pinpoint warnings inside a half hour. Warnings that reach those in harm's way, in time for them to take life-saving action. For hazards such as earthquakes, for which forecasts are not yet in prospect, this means good mapping of seismic zones, extending to the smallest possible scales. Along coastlines—vulnerable to winter storms, hurricanes, and seismically triggered tsunamis—this requires special monitoring technologies and an extra measure of vigilance.

Note that all this can give the public no more than a fighting chance. It's up to each of us to be knowledgeable about the hazards around us and those actions that give us and those we care about the best chance of survival.

The pursuit of happiness *in the face of hazards?* Among other things, perhaps this implies that:

Home ought to be the safest place to be . . . not just a point of embarkation for the family evacuation. This means effective land use and building codes. And given the dependence of every home today on critical infrastructure—hard infrastructure such as electricity, communications, natural gas, water, transportation, sewage disposal, and soft infrastructure such as health care, financial institutions, schools, and much more—that critical infrastructure should survive as well.

A job to return to after the hazard has come and gone. Many families and individuals survive disasters only to find that their community economy has been disrupted in a lasting way. Many small businesses are destroyed by such events. Others survive initially only to fail over time because their customer base has been hard hit. Very few small businesses which close their doors as a result of disasters ever reopen. Many disaster survivors escape injury entirely only to find that this lack of a job, a sine qua non for normalcy—rather than the immediate disaster as such—is a major contributor to the pain and suffering that survivors experience.

Natural disasters stay natural. All too often, flood waters pass through a town or city only to be transformed into a slurry of animal carcasses, toxic chemicals, and waste. As earthquakes, high winds, and flooding cause structural failure they rupture gas lines and down electrical wiring, starting fires which are often more dangerous than the original events themselves. In the San Francisco earthquake of 1906, the ground shook for 45 seconds; the fires burned for three days and caused most of the death toll. The same would be true of the 1995 Kobe earthquake, nearly a century later. Last year's Great Tohoku earthquake and the resulting tsunami did tremendous damage to Japan in the first hour, but the damage to the Fukushima nuclear reactors threatens to be more costly and enduring. Often, even after small-scale events such as tornadoes, the simple task of waste removal from the site goes on for a year or more.

Again—a chance to survive the immediate danger, a home we can defend, a job that's still there even in the aftermath, and an environment that's whole and unpolluted—this is the happiness we pursue on this hazardous Earth. And these are some of the reasons we institute our federal, state, and local governments.

It's part of the reason we fund NOAA and other Commerce agencies, USGS and other agencies from Interior, the Department of Homeland Security, independent agencies such as NASA, NSF, and yes . . . EPA. And it's part of the reason why

". . .for the support of this Declaration, with a firm reliance on the protection of divine Providence, we mutually pledge to each other our Lives, our Fortunes and our sacred Honor."

NEW MEMBERS

The Council has approved the election of the following candidates to the grade of **Full Member:**

Edward Addison
Rashid A. Ahmad
Stephanie R. Allison
Clement A. Alo
Jose-Henrique G.M. Alves
Drew Anderson
Toshinori Aoyagi
Heather M. Archambault
Andrew T. Baglini
Nikolaos Bakas
Logan Barnett
Richard Barnhill
Archer L. Batcheller
Ashley Batey
Andrew J. Bennett
Jonathan R. Berry
Stefano Berti
Matthew Biddle
Catherine A. Bodak
Giovanni Botta
Lindsey A. Breitzman
Wolfgang Brettschneider
Norman E. Breuer
Christine L. Brown
Lauren M. Brown
Vankita Brown
Jim Buitt
Stephen D. Burt
Kun-Young Byun
James C. Caldwell
Guylaine Canut
Neil E. Caporaso
Simon A. Carn
Jennifer M. Cederle
Hsin-I Chang
Lee S. Chesneau
Ben H. Chou
Kao-Shen Chung
Jacob R. Cobb
Michael T. Coe
Leslie R. Colin
Paulo A. Costa
Susanne Crewell
Erik T. Crosman
Johannes Dahl
Meghan Dalton
Bob Dattore
Daniel DePodwin
Robert Dickinson
Rob Dies
Jaime A. DiFulvio
Shari Dixon
Kyle Dodd
Heather A. Dominik
Robert Dunn
Gregory D. Dutra
Geoffry Eberle
Frederick A. Eckel
Ian Eisenman
Greg A. Eisman
Michael T. Estime
Kevin M. Eubank
Allen C. Evans
Tara M. Fardellone
David Feller
Chris Fenimore
Todd R. Ferebee
Craig R. Ferguson
Richard D. Foot
Jason C. Furtado
Olivier Gagnon
Anita M. Gajdecki
Jose M. Garcia Jr.
Robert A. Garcia
Michael C. Geary
Richard P. Giard
Peter H. Gleick
Aaron J. Glenn
Mara G. Gonzalez
Briana J. Gordon
Eric Gordon
Eugenio Gorgucci
Jeffrey S. Grabon
Steven J. Greybush
Kevin M. Grise
Toby P. Grubbs
Xiaofeng Guo
Maher A. Haddad
Andrew B. Hagen
Lee D. Hawkness-Smith
Xianfeng He
Brent C. Hedquist
Kevin S. Henderson
Randall J. Hergert
Anthony C. Hess
Jeffrey Hess
Edward P. Hildebrand
Peter Hogarth
Jeffrey B. Hood
Larry J. Hopper Jr.
William J. House
John G. Houston
Melissa Huffman
Eli M. Huven
Edward J. Hyer
Kosuke Ito
Ryan W. Jakubowski
Richard F. Jaworski Jr.
Liwei Jia
Zhangyan Jiang
Xin Jin
Justin E. Jones
Kathy A. R. Jones
Nicholas J. Juliano
Derrick A. Kania
Sarah B. Kapnick
Edward J. Kearns
Kelly M. Keene
Brandon W. Kerns
Gerard S. Ketefian

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

Nick Adams
Eric A. Aligo
Bonnie Anderson
Bjorn C. Backeberg
Megan M. Bela
Anwesa Bhattacharya
Michael T. Bilder
Jonathan Brazzell
Katherine L. Burch
Christopher Cromeans
Areana Flores
Brody Fuchs
Abebe S. Gebregiorgis
Maria Gehne
Darnell G. Gillie
Russell H. Glazer
Jennifer Henderson
Eduardo Herrera
Leslie R. Hill
Spencer A. Hill
Drew M. Hock
Eric Holloway
Johnna Infanti
Jenny Kafka
Gerard Kilroy
Ji-in Kim
Joseph Knapik
Timothy Logan
Konstantinos Menelaou
George N. Mwaniki
Andrew Norwood
Lauren Padilla
Kurtis Pinkney
William R. Ryerson
Michael R. Saenz
Zachariah Silver
Jeffrey D. Strong
Wenxiu Sun
Matt Taraldsen
Anthony Testino
Janel R. Thomas
Ricardito Vargas Jr.
Ricci Yue
Christopher M. Zarzar

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

John B. Barone
Paul C. Fisher
Julimarie Thomas
Vanessa L. Van Sciver
Lindsey M. Waddell
David O. Weller
Kueyson Yee

NEW MEMBERS

Daehyun Kim
Hyokyung Kim
Seon Tae Kim
Christine Kirchhoff
Kelly Klima
Klaus Kordowski
Vladimir N. Krupchatnikov
Atsushi Kudo
Jong Seong Kug
Kevin W. LaCroix
E. S. Lanham
Guillaume Lapeyre
Erik D. Larson
Sanghun Lim
Samuel R. Lokensgard
Franklin T. Lombardo
Stephanie L. Ludwig
Katherine A. Lundquist
Brian Magi
Scott G. Magnan
Liora Malki-Epshtein
Carole A. Mandryk
Edson R. Marciotto
Evan Mason
Frank McCathran
Angel McCoy
Jordan T. McLeod
Elizabeth J. McMichael
Gregory J. McQuoid
Shawn Mechelke
Shanna Mendiola
Paul Meshekow
Nicholas D. Metz
James T. Monroe
Kaitlyn M. Moore
James A. R. Morrison Sr.
Kathryn W. Mozer
Kunihiro Naito
Bruno Nardi
Amanda M. Nelson
Aloisia A. Nuijens
Travis A. O'Brien
Jesse O'Neal
Kazunori Ogohara
Salvatore C. Orobello
Stephen Owens
Jon Oxtoby
John A. Paquette
Josh Park
ShinJu Park
Nicholas A. Parker
Peitao Peng
Michael Perrotte
Alexander Petersen
Brittany L. Petrarca
Mike Piatek-Jimenez
Jared D. Piepenburg
Justin Pletsch
Gregory F. Pollak
Renee Raatz Frazier
Alexander Radkevich
Gary N. Reinecke
Jared J. Rennie
Charles Retallack
Hank Rinehart
Patrick M. Rosborough
Angela K. Rowe
Mauricio N. Saldivar
Thomas P. Sandquist
James W. Scheideler
Bradley Schneider
John P. Schneider
Carl J. Schreck III
Jennifer Schuller
Craig S. Schwartz
Bhaswar Sen
Maurice A. Shamell
Daniel J. Sheehan
Kathryn A. Shontz
Kristofer Shrestha
Chris A. Shuma
James Slavin
Carmen Snyder
Derrick William Snyder
Michael Sollom
Scott R. Springer
Pierre St-Laurent
David St. John
Cal Steiner
Anne Marie K. Stoner
Elizabeth Suess
James Taeger
Lin Tang
Lyndsay Tapases
Mackenzie L. Tepel
Devin Thomas
William W. Todd
Richard Ullman
Matthew S. Van Den Broeke
Adrienne K. Veilleux
Daniel Veren
Gabriele Villarini
Federico M. Waisman
Brandon Wallis
Aihui Wang
Sheng-Hung Wang
Bill Ward
Kurt T. Warner
Elizabeth Welliver
Matthew J. Widlansky
Andrew E. Wilkins
Robert D. Wonderling
Waid S. Woodruff
Luciano Xavier
Elaine L. Yang
Duick T. Young
Feng Zhang
Judith M. Ziemnik

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

Michael Abbott
Craig D. Buchanan
Laura Danielson
Alexander G. Fisher
Michael Fishman
Matthew R. Gallagher
Chris Galli
Anthony A. Guiffrida
Bryan Hanssen
Steven Honey
Louis L. Johnson
Simon G. Kraatz
Tyler L. Kreidler
Bruce E. Kurtz
Steven A. Long
Michael A. Scott
Christopher Shore
Joel B. Smith
Chris Thomas
Steven H. Willans
Bryan H. Wood

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

Carolina Bieri
Noah C. Chalker
Laura G. Dombkowski
Caroline Donelan
Benjamin Z. Dovek
David J. Downey
Jonathan Z. Falk
Lucas R. Gallo
Alexander M. Henny
Zachary Herring
Hannah R. Hitchcock
Jena P. Howard
Margaret Klug
Jacob Krueger
Joshua D. Lee
Clare Maher
Caroline A. Medlin
Nic M. Petrykowski
Scot M. Pilie
Jackie M. Pursell
Louise V. Ruid
William J. Shannon
Aaron L. Stevens
Ryan C. Tawil
Dalton J. Van Stratten
Bradley B. Zylstra

NEW MEMBERS

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

Megan Absher
Ryan E. Adams
Stephanie Adams
Gonzalo A. Agudelo Jr.
Christian K. Akpanya
Seyed H. Alemohammad
Daniel C. Alexander
Gail L. Altieri
George R. Alvey
Hilary L. Ames
Samuel M. Ames Jr.
Nichelle A. Anderson
Alexandra Anderson-Frey
Christina G. Anthony
Gilles Arfeuille
Hannah E. Attard
Jeff D. Auger
Nathan Auping
Alex T. Avalos
Monica Yeliss Ayala
Lindsey Baird
Carlos A. Ballesteros
Rebekah I. Banas
Amanda M. Bandurski
Stephanie Barichello
Brian Barr
Justin M. Barrick
Chelsea N. Bartlett
Carly Baumann
Kyle T. Beck
Katherine B. Benedict
Joseph R. Bennett
Lyndsey Bennett
Mark D. Benoit
James L. Bielli
Kevin A. Biernat
Jason Blumenfeld
Kristen N. Bond
Paloma Borque
Samantha G. Borth
Brandon M. Bouche
Allyson Bowden
Adam R. Bowerman
Jaron M. Breen
Amanda S. Brioche
Julien Brun
Michael R. Bueti
David Burcicki Jr.
Uriah Burhans
Michael Butler
Nikki Byers
David Callicutt
John L. Cambareri
Bart J. Carr
Brittany Carson
Alexandra L. Caruthers
Wilson Castellano
Tyler Castillo
Nicholas R. Cavanaugh
Junyi Chai
Jerrod L. Chambers
Haonan Chen
Ru Chen
Matthew J. Chonka
Margaret Christopher
Lyndee R. Clark
Rob Clements
David A. Coates
Brice Evan Coffer
Jeff Cohen
Manda B. Cole
Hanna I. Colliander
Jose G. Colon-Reyes
Jose M. Cora
Jose A. Cordero-Gonzalez
Levi Cowan
Chris J. Cox
David A. Cox
Landen L. Crespin
Ewan C. Crosbie
Angela Crowder
Cui Cui
Elisabeth A. D'Amore
Robert D'Arienzo
Meredith Dahlstrom
Zachary Daniels
Roderick A. Dauzat Jr.
Robert David
Aaron Davis
Nick R. Davis
Adam Michael Dawson
Saul D. Ddumba
Josef Decker
Damien Decremer
Jade DeMers
Megan Demmert
Amanda M. DePasquale
Patrick T. Devore
Martin A. Diaz
Paul Dinwoodie
Ashley Dixon
Gergely Dolgos
Brittani DuBose
Jennifer L. Dums
Andrew Dzambo
Patrick Edmonds
Taylor Egan
Zachary C. Eichholz
Rachel Eidelman
William Jason Elser
Ashley N. Felts
Nan Feng
Ya-Chien Feng
Alex Ferguson
Angela M. Ferra
Michael S. Fischer
Tiffany A. Fisher
Lizxandra Flores Rivera
Annette Foerster
Andrea M. Franco
Sean Freeman
Aaron R. Freson
Maegen M. Fried
Drew Fultz
Frank C. Gaetano
Cen Gao
Kun Gao
Erica Gentsch
Brianne M. Gerber
Natasha Gibbs
Timothy J. Gibbs
Jennifer L. Gil
Daniel M. Gilford
Bradley P. Goodwin
Thomas M. Gowan
Matthew F. Gray
Tami M. Gray
Christopher R. Gregg
Katelyn E. Grove
Corey Guastini
Matthew J. Hairston
Martin C. Hale
Dianne E. Hall
Joseph R. Halvorson
Nathan M. Hamet
Jonathon Hamilton
Zachary R. Hansen
Joseph C. Hardin
Kimberly A. Hartmus
Timothy Hatlee
Briana Hawras
Jian He
David Heeps Jr.
Andrew Heirty
Emily Heller
Gavin Heller
Ben Henley
Michael A. Herrera
Denise Hertwig
Travis W. Hill
Sage M. Hiller
Noel G. Hilliard
Ericka Hines
Bobby Hinton
Michael Hirschberger
David G. Hirst
Richard Hoadley
Nicholas Hochmuth
Laura E. Hodgens
Patrick G. Hogan
Helen Holt
Laura G. Holtzman
Farnaz Hosseinpour
Tsung-Lin Hsieh
Timothy W. Humphrey
Todd C. Hunter
Marc A. Jacobs
Damaris R. Jaime
Emanuel Janisch
Schinook J. Jeansonne
Shelley Jeltema
Jerry Y. Jien
Jessica D. Johnson
Amanda Jones
Justin D. Joplin
Cheuk Yi Joseph
George P. Kablick III
Taylor Kanost
Alexandra Karambelas
Andrea M. Karelitz
Chris Karmosky
Jeremy L. Katz
Melissa Kaufman
Aaron Kaulfus
Alpana Kaushiva
Rachel L. Kelley
Gina Kelshaw
Steven D. Kerr
Masoud Khoshsima
Ryan Kiefer
Hannah C. Kight
Matthew A. King
Robyn N. King
Joe Kleiman
Sean C. Klipple
Andrew J. Koehler
Adam Kohn
Rebecca Kollmeyer
Cassandra C. Kreckman
John R. Kummer
Michael T. Kyle
Zachary M. Labe
Brian J. Lada
Alexander J. Lakocy
Miriah Denae Lamping
Stephen Lanciani
Katie E. Landry
Isabela Le Bras
Alexander D. Lee
Kyunghwa Lee
Wannee J. Lewis
Ming-Yeng Lin
Amanda Lindquist
Ryan C. Lingo
Yan Liu
Irenea C. Lodangco
Jesus M. Lopez
Heather M. Lucier
Javier Lujan
Cecilia Lundquist
Holly Lussenden
Kelsey Lyons

NEW MEMBERS

Anthony W. Lyza
Derek Ray Maassen
Viviana Maggioni
Corey D. Maller
Jesse L. Manzi
Jeffrey Mart
David L. Martin
Edith Martinez
Greg A. Mastroianni
Morgan L. Matchett
Alyssa A. Matthews
Lindsay C. Maudlin
Gregg W. McCambley
Casey McClure
Christina S. McCluskey
Anthony C. McCullough
Cassie M. McIntyre
Thomas B. McKenzie III
Maureen K. McKinney
Rachel McLoughlin
Manuel S. Medina
Rui Mei
Caleb N. Meute
Trisha D. Michael
David Mikolajczyk
Audra Miller
Madeline Miller
Kumar Vijay Mishra
Jake Mittelman
Takuya Miyagawa
Yanelly Molina
Matthew D. Moore
Annareli Morales
Stephen Morgan
Mackenzie M. Morris
Jordan L. Morrow
Tyler D. Morrow
Janelle C. Mudgett
Francis T. Mullen
Kevin W. Murphy
Matthew S. Muscato
Stephanie N. Nance
Robert J. Navarro
Ryan R. Neely III
Kyle Nelson
Timothy C. Nelson
Meredith A. Nichols
Kimberlee E. Nighelli
Arielle L. Nixon
Rose Njoroge
Melissa Nord
Caroline Normile
Parker Norton
Kelly M. Nunez
Ryan Oates
Steve Olson
Rie Onodera
John Orcutt
Ana C. Ordonez
Brandon M. Orr
Ana Ortiz
Jose A. Ortiz
Krzysztof Orzel
Elizabeth Orzulak
Tashiana Osborne
Stephen Osinski
William J. Pace III
James Palac
Nichole Pallan
Joshua M. Palmer
Bowen Pan
Nichole L. Pate
Pratik Patel
Anamaria Perez
Walter A. Perkins
Melissa G. Pierce
Claudine M. Pierz
Candace C. Pinnisi
Michael Pirhalla
Derek I. Podowitz
Brian W.F. Popick
Jerry M. Post
Jody L. Pradelski
Blake S. Pranger
Sarah R. Pritchard
Sally Pusede
Aishwarya Raman
Michelle R. Ramotowski
Nivash Rampersad
Elizabeth M. Ray
Ariana C. Reese
Cecilia M. Reeves
Adam Reiersgaard
Michael C. Rencurrel
Alexander M. Rettof
DeVondria D. Reynolds
Alan Rhoades
Michael J. Rieger
Jacob A. Riley
Judimar Rios Rivera
Jared M. Rising
Glorianne M. Rivera Santiago
Scott Roberts
Alyssa Robinette
Matthew C. Roby
Derek A. Romanyk
Karl F. Ronning
Katie Rourke
Johna E. Rudzin
Niklas H. Rueter
Richard Frank Russell III
Kelly E. Ryan
Rachel M. Ryan
Nora I. Saari
Samaneh Sabetghadam
Babak Safa
Anthony D. Sambucci
Richard R. Sample II
Jose A. Sanchez-Rodriguez
Nitza A. Santiago-Figuero
Matthew S. Saunders
Kyle M. Schanus
Adam Schnapp
Anna I. Schneider
Michael A. Schneider
Laura Schutte
Kayla M. Schwalbe
Adam C. Schwantes
Jeremy Scott
Brannon A. Seay
Cameron K. Self
Heather M. Sepulveda
Frances A. Sewell
Devin Clark Shaman
Tom L. Shankle Jr.
Dustin Shea
Rebecca A. Sheperd
Stephen Shiveley
Stephanie Sine
Taleena Sines
Joshua R. Sisley
Benjamin A. Sisskind
Lauren M. Slawsky
Kristin M. Smedley
Dakota C. Smith
Molly B. Smith
Russell H. Smith
Ryan C. Smith
Brittanny Snyder
Elizabeth R. Somers
Shi Song
Trevor J. Sonnier
Alessio C. Spassiani
Mark Sperduti
Brandon James Spinner
Elizabeth R. Staatz
George R. Stackpole V
Michael J. Stahlman
Iain D. Stewart
Nicholas P. Stewart
Robert Stoflet
Douglas Stolz
William R. Strickler
Kevin C. Stump
Stacey R. Sueoka
Shanshan Sun
Shuaiqi Tang
Jing Tao
Wei Tao
Erik S. Taylor
Shayne T. Taylor
Amanda Terborg
Erin E. Thomas
Alexandra Thompson
Josh Thompson
Danielle C. Thorne
Camellia Tipton
Kaitlin Togliatti
Ana P. Torres
Maribel Torres
Dany Tran
David J. Tupman
William Turner IV
Laura Twidle
Timm Uhlmann
Alexandra Unger
Jessica Van Meter
Jacob T. Vancil
Lance VandenBoogart
Peter Veals
Eder P. Vendrasco
Joshua D. Verbeten
Tarun Verma
Luke Victor
Tania Villanueva-Ayala
Ryan J. Voelz
Casey L. Vogt
Stephanie C. Waldref
Carissa Walker
Sheana M. Walsh
Thomas C. Ward
Phillip J. Ware
Megan Washington
Dawn M. Wedig
Brian M. Wehner
Erik J. Weiksner
Zachary L. Weiner
Bradley Wells
Elizabeth M. Whalley
David F. Wheeler III
Joshua A. Whisnant
Sean White
Zachary B. Wienhoff
David J. Wiersema
Joseph L. Wilkins
Bryce R. Williams
Castle A. Williams
Kathleen E. Willmot
Samantha Wills
Andrew B. Wilson
Thomas Winesett
Max Wiosna
Monika A. Wnuk
Rochelle P. Worsnop
Nicolas JG Wright
Andrew J. Yarosh
Alex B. Young
Gan Zhang
Honghai Zhang
Steven E. Zimmerman
Kyle M. Ziolkowski
Nicholas B. Zweber

CALENDAR OF MEETINGS

The Call for Papers and Calendar sections list conferences, symposia, and workshops that are of potential interest to AMS members. **Complete information about events listed in the calendar can be found on the meetings page of the AMS Web site, 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

2012

MAY

30th Conference on Agricultural and Forest Meteorology, 27 May–1 June, Boston, Massachusetts
Abstract deadline: 30 January 2012
Preregistration deadline: 16 April 2012
Manuscript deadline: 1 July 2012
Initial Announcement Published: Nov. 2011

First Conference on Atmospheric Biogeosciences, 27 May–1 June, Boston, Massachusetts
Abstract deadline: 30 January 2012
Preregistration deadline: 16 April 2012
Manuscript deadline: 1 July 2012
Initial Announcement Published: Nov. 2011

25th Conference on Weather and Forecasting (WAF) and 21st Conference on Numerical Weather Prediction (NWP) Jointly with the 46th Canadian Meteorological and Oceanographical Society (CMOS) Congress 2012, 29 May–1 June, Montreal, Quebec, Canada
Abstract deadline: 15 February 2012
Initial Announcement Published: Oct. 2011

JULY

20th Symposium on Boundary Layers and Turbulence, 8–13 July, Boston, Massachusetts
Abstract deadline: 5 April 2012
Preregistration deadline: 1 June 2012
Manuscript deadline: 13 August 2012
Initial announcement published: Aug. 2011

18th Conference on Air–Sea Interaction, 8–13 July, Boston, Massachusetts
Abstract deadline: 5 April 2012
Preregistration deadline: 1 June 2012
Manuscript deadline: 13 August 2012
Initial announcement published: Aug. 2011

AUGUST

10th Symposium on the Urban Environment and Eight International Conference on Urban Climate (ICUC8), 6–10 August, Dublin, Ireland
Abstract deadline: 20 January 2012
Initial announcement published: Nov. 2011

40th Broadcast Meteorology Conference, 22–25 August, Boston, Massachusetts
Abstract deadline: 23 March 2012
Preregistration deadline: 2 July 2012
Initial Announcement Published: Dec. 2011

15th Conference on Mountain Meteorology, 20–24 August, Steamboat Springs, Colorado
Abstract deadline: 20 April 2012
Preregistration deadline: 9 July 2012
Manuscript deadline: 20 September 2012
Initial Announcement Published: Nov. 2011

NOVEMBER

26th Conference on Severe Local Storms, 5–8 November, Nashville, Tennessee
Abstract deadline: 10 August 2012
Preregistration deadline: 7 September 2012
Manuscript deadline: 7 December 2012
Initial announcement published: Aug. 2011

2013

JANUARY

12th Annual AMS Student Conference: Expanding Weather and Climate Prediction—Taking Geosciences to the Next Level, 5–6 January, Austin, Texas
Abstract deadline: 1 October 2012
Registration deadline: 18 December 2012
Initial announcement published: Feb. 2012

***Robert A. Duce Symposium, 8 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***29th Conference on Environmental Information Processing Technologies (formerly known as Interactive Information Processing Technologies, IIPS), 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***27th Conference on Hydrology, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

*An exhibit program will be held at this meeting.

***25th Conference on Climate Variability and Change, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***22nd Symposium on Education, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***20th Conference on Applied Climatology, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***19th Conference on Planned and Inadvertent Weather Modification, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: May 2012

***17th Conference on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS–AOLS), 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***16th Conference on Aviation, Range, and Aerospace Meteorology (ARAM), 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***16th Conference of Atmospheric Science Librarians International (ASLI), 6–10 January, Austin, Texas**
Abstract deadline: 1 October 2012
Preregistration deadline: 1 December 2012
Initial announcement published: TBD

***15th Conference on Atmospheric Chemistry, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***11th Conference on Artificial and Computational Intelligence and its Applications to the Environmental Sciences, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

* An exhibit program will be held at this meeting.

***11th Symposium on the Coastal Environment, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***11th History Symposium, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***10th Conference on Space Weather, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: May 2012

***Ninth Annual Symposium on Future Operational Environmental Satellite Systems, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***Eighth Symposium on Policy and Socio-Economic Research, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***Sixth Conference on the Meteorological Applications of Lightning Data, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***Sixth Symposium on Lidar Atmospheric Applications, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: May 2012

***Sixth Annual CCM Forum: Certified Consulting Meteorologists, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: April 2012

***Fifth Symposium on Aerosol–Cloud–Climate Interactions, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***Fourth Conference on Environment and Health, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***Fourth Conference on Weather, Climate, and the New Energy Economy, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***Third Symposium on Advances in Modeling and Analysis Using Python, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***Third Conference on Transition of Research to Operations: Successes, Plans, and Challenges, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***Second Symposium on Planetary Atmospheres, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: May 2012

***First Annual Symposium on Improving Communication, Collaboration and Response to Weather Forecasts and Warnings, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: April 2012

***First Symposium on the Weather and Climate Enterprise, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

***Special Symposium on Advancing Weather and Climate Forecasts: Innovative Techniques and Applications, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: April 2012

***Special Symposium on the Joint Center for Satellite Data Assimilation, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: May 2012

***Special Symposium on the Next Level of Predictions in Tropical Meteorology: Techniques, Usage, Support, and Impacts, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

* An exhibit program will be held at this meeting.

***Symposium on Prediction of the Madden–Julian Oscillation, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: April 2012

***Symposium on the Role of Statistical Methods in Weather and Climate Prediction, 6–10 January, Austin, Texas**
Abstract deadline: 1 August 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: May 2012

***IMPACTS: Major Weather Events and Impacts of 2012, 8 January, Austin, Texas**
Abstract deadline: 15 October 2012
Preregistration deadline: 1 December 2012
Manuscript deadline: 6 February 2013
Initial announcement published: Feb. 2012

MEETINGS OF INTEREST

2012

APRIL

Third Annual Great Lakes Atmospheric Science Symposium (GLASS), 28 April, Oswego, New York

MAY

32nd NATO/SPS International Technical Meeting on Air Pollution Modelling and its Application, 7–11 May, Utrecht, the Netherlands

Fourth WCRP International Conference on Reanalyses, 7–11 May, Silver Spring, Maryland

JUNE

16th International Symposium for the Advancement of Boundary Layer Remote Sensing, 5–8 June, Boulder, Colorado

Fifth Chaotic Modeling and Simulation International Conference (CHAOS 2012), 12–15 June, Athens Greece

Croatian–USA Workshop on Mesometeorology, 18–20 June, Zagreb, Croatia

JULY

16th International Conference on Clouds and Precipitation, 28 July–3 August 2012, Leipzig, Germany

AUGUST

International Radiation Symposium 2012, 6–10 August, Dahlem Cube, Berlin, Germany

International Symposium on Nowcasting and Very Short Range Forecasting, 6–10 August, Rio de Janeiro, Brazil

SEPTEMBER

2012 EUMETSAT Meteorological Satellite Conference, 3–7 September, Sopot, Poland

12th EMS Annual Meeting & 9th European Conference on Applied Climatology (ECAC), 10–14 September, Łódź, Poland

Third International Conference on Earth System Modelling, 17–21 September, Hamburg, Germany

OCTOBER

Fourth Tri-State Weather Conference, 13 October, Danbury, Connecticut

NOAA's 37th Climate Diagnostics and Prediction Workshop, 22–25 October, Fort Collins, Colorado

2012 Conference on Intelligent Data Understanding, 24–26 October, Boulder, Colorado

2013

JUNE

Second China–U.S. Symposium on Meteorology, 24–28 June, Qingdao, China

* An exhibit program will be held at this meeting.

CALL FOR PAPERS

CALL FOR PAPERS

19th Conference on Planned and Inadvertent Weather Modification, 6–10 January 2013, Austin, Texas

The 19th Conference on Planned and Inadvertent Weather Modification, sponsored by the American Meteorological Society, and organized by the AMS Committee on Weather Modification, will be held 6–10 January 2013, as part of the 93rd AMS Annual Meeting in Austin, Texas. Preliminary programs, registration, hotel, and general information will be posted on the AMS website (www.ametsoc.org/meet/annual/) in late-September 2012.

The theme for the 2013 AMS Annual Meeting is "Taking Predictions to the Next Level: Expanding Beyond Today's Weather and Climate Forecasts and Projections." The interdisciplinary aspects of our science are also being emphasized. Following this theme, the 19th Conference on Planned and Inadvertent Weather Modification is soliciting papers over a wide range of traditional and interdisciplinary topics, including those that address the prediction needs of water resource managers and other decision-makers. Joint sessions are planned, and papers are encouraged in the following areas:

- The feasibility, risks, costs, policy implications, and ethical and political dimensions of global radiation intervention (with the 25th Conference on Climate Variability and Change);
- Impacts of anthropogenic aerosols on clouds, precipitation, circulation, and severe storms (with the Fifth Symposium on Aerosol–Cloud–Climate Interactions);
- Aerosol–cloud interactions in weather forecasting (with the Fifth Symposium on Aerosol–Cloud–Climate Interactions);
- The impacts of the urban environment on precipitation and heat waves (with the Board on the Urban Environment);
- The detection of planned and inadvertent changes in clouds and the weather (with the Probability and Statistics Special Symposium).

As always, papers on traditional topics in planned and inadvertent weather modification also are sought, including, but not limited to

- physical evidence of cloud seeding effects and general weather modification aspects;
- hydrological applications to weather modification projects and evaluation;
- recent developments in understanding natural cloud processes and aerosol–cloud interactions relevant to weather modification;
- the development and refinement of conceptual models, including those for enhancing precipitation and mitigating the severity of storms;
- applications of numerical models to planned and inadvertent weather modification topics;
- societal and economic effects of anthropogenic impacts on weather and climate.

Please submit your abstract electronically via the web by *1 August 2012* (refer to the AMS web page at 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 late-September 2012. 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 3 MB) electronically by 6 February 2013. All abstracts, extended abstracts, and presentations will be available on the AMS website at no cost.

For additional information please contact the program chairperson, Dan Breed, National Center for Atmospheric Research, Boulder, Colorado (e-mail: breed@ucar.edu). (5/12)

CALL FOR PAPERS

11th History Symposium, 6–10 January 2013, Austin, Texas

The Eleventh History Symposium, sponsored by the American Meteorological Society, and organized by the AMS History Committee, will be held 6–10 January 2013, as part of the 93rd AMS Annual Meeting in Austin, Texas. Preliminary programs, registration, hotel, and general information will be posted on the AMS website (www.ametsoc.org/meet/annual/) in late-September 2012.

The theme for the 2013 AMS Annual Meeting is "Taking Predictions to the Next Level: Expanding Beyond Today's Weather and Climate Forecasts and Projections." In keeping with this year's overarching AMS theme, the History Committee solicits papers that address the historical development and implications of weather and climate forecasts with special emphasis on contemporary water and drought issues, space weather prediction, history and development of hurricane observation and forecasting, as outlined below. Papers may be broadly conceived, in any time period or cultural context. The History Committee invites discourse between atmospheric scientists, historians of science, science librarians and archivists, social scientists, geographers, and other disciplines that intersect history and the atmospheric sciences.

This year papers are solicited on

- contemporary regional water and drought issues viewed through the lens of history—how history has illuminated and informed present decision making and science. This could include, but is not limited to, great droughts of the 1950s and 1930s, Texas and regional dust bowl history, historical flooding events of the region (joint with Conference on Hydrology, History is lead)
- historical perspectives in space weather prediction (joint with 10th Conference on Space Weather, Space Weather is lead)
- historical perspectives on predictions and the decision making process in tropical meteorology, examined with respect to all tropical meteorology forecast systems, and including historical development of governing agencies responsible for operations and decision processes (joint with Special Symposium on the Next Level of Prediction in Tropical Meteorology, Tropical Meteorology is lead)
- general contributions on historical perspectives on weather, climate, and natural history issues of the region and, specifically, to continue the focus on hydrology/water issues and history and development of hurricane observation and forecasting. May also include historical development of agencies, instrumentation, and analysis tools related to forecasting science. (History Symposium, General sessions)

Please submit your abstract electronically via the web by *1 August 2012* (refer to the AMS web page at 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 late-September 2012. 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 *6 February 2013*. All abstracts, extended abstracts and presentations will be available on the AMS website at no cost.

For additional information please contact Jean Phillips, History Committee Chair, Space Science and Engineering Center, University of Wisconsin—Madison, 1225 W. Dayton Street, Madison, WI 53706 (e-mail: jean.phillips@ssec.wisc.edu). (2/12; r5/12)

CALL FOR PAPERS

10th Conference on Space Weather, 6–10 January 2013, Austin, Texas

The Tenth Conference on Space Weather (10th CSW), sponsored by the American Meteorological Society, and organized by the AMS

STUDENT TRAVEL GRANTS

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

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

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

For more information and to complete an application form, please visit the AMS website at www.ametsoc.org.

Committee on Space Weather, will be held 6–10 January 2013, as part of the 93rd AMS Annual Meeting in Austin, Texas. Preliminary programs, registration, hotel, and general information will be posted on the AMS website (www.ametsoc.org/meet/annual/) in late-September 2012.

The theme for the 2013 AMS Annual Meeting is "Taking Predictions to the Next Level: Expanding Beyond Today's Weather and Climate Forecasts and Projections." Over the past 60 years the meteorological community has made tremendous strides in making prediction a fundamental part of its scientific and operational/service heritage through the development and application of complex numerical models involving the atmosphere, ocean, land, and cryosphere components of the Earth System. This theme will serve as a catalyst for the 2013 AMS Annual Meeting by focusing the attention of the research and operational communities, including those who are involved in accelerating the transition of research results into operations. Furthermore, the increasing use of predictions by decision makers throughout federal, state, and local emergency management government agencies and by private/commercial sectors will serve as an important component for this annual meeting along with the extension of predictive capabilities into a broader domain, including public health, food security, air and water quality, alternative energy, navigation, communication, and responses to climate trends.

This year's theme is highly appropriate for the 10th CSW. Compared to numerical weather prediction, the space weather discipline is still in its infancy and prediction capabilities are not as mature and sophisticated as what have been achieved for terrestrial weather. However, there have been a number of advances in our understanding of the Sun–Earth System, operational space weather models, and ground- and space-based data sets. Using meteorology as an example, the space weather community is in the early stages of delivering improved forecast capabilities for a variety of space weather applications. The 10th CSW will highlight those burgeoning new capabilities and reflect on advances in science and prediction over the past decade since the first Space Weather Symposium was held at the Annual AMS Meeting.

This year papers are solicited on

- advances in space weather nowcasting and forecasting, and associated metrics
- advances in space weather instrumentation and models
- new data sources and products
- historical perspectives in space weather prediction (joint with History Conference)
- space weather transition plans, challenges, opportunities (joint with 3rd Research to Operations Conference)
- general contributions

Please submit your abstract electronically via the web by *1 August 2012* (refer to the AMS web page at 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 late-September 2012. 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 6 February 2013. All abstracts, extended abstracts, and presentations will be available on the AMS website at no cost.

For additional information please contact the program chairperson(s), Bob McCoy (e-mail: rpmccoy@alaska.edu) or Genene Fisher (e-mail: Genene.fisher@noaa.gov). (5/12)

CALL FOR PAPERS

Sixth Symposium on Lidar Atmospheric Applications, 6–10 January 2013, Austin, Texas

A Symposium on Lidar Atmospheric Applications, sponsored by the American Meteorological Society and organized by the AMS Committee on Laser Atmospheric Studies, will be held 6–10 January 2013 as part of the 93rd AMS Annual Meeting in Austin, Texas. Preliminary programs, registration, hotel, and general information will be posted on the AMS website (www.ametsoc.org/meet/annual/) in late-September 2012.

Lidar probing of the atmosphere has progressed from research phase and is being applied to many of today's environmental and climate solutions. Lidar-based research in fundamental measurements of aerosols, clouds, water vapor, temperature, trace gas chemistry, wind, and process-based studies have become part of the standard meteorological instrumentation. In addition, the basic technologies have matured and their applications have started to emerge as ground-based networks and space-based long-term monitoring tools to aid in climate-related research. This symposium is intended to bring together and review recent advances in lidar-based atmospheric application programs and activities.

The meeting will consist of a number of invited review talks and contributed papers and posters. The scope of this symposium is lidar application studies, and in particular those that are process-based applications that contribute to studying the state and composition of the atmosphere, including the clouds, aerosols, radiatively important gases, and thermodynamic structures of the troposphere and stratosphere. Papers that address this general theme of lidar atmospheric applications and, in particular, process-based applications are solicited. Sessions are anticipated on lidar networks, space-borne lidars, automated operational lidars, long-term climate observations, air pollution applications, lidar data assimilation in numerical weather models, and emerging lidar methods in addressing atmospheric issues. Of particular interest is the use of lidars in conjunction with other instrumentation (e.g., radar-lidar techniques) in pollution, climate, and weather studies. Participants with additional suggestions for the program are encouraged to contact the program chairperson.

The theme for the 2013 AMS Annual Meeting is "Taking Predictions to the Next Level: Expanding Beyond Today's Weather and Climate Forecasts and Projections." Over the past 60 years the meteorological community has made tremendous strides in making prediction a fundamental part of its scientific and operational/service heritage through the development and application of complex numerical models involving the atmosphere, ocean, land, and cryosphere components of the Earth System. This theme will serve as a catalyst for the 2013 AMS Annual Meeting by focusing the attention of the research and operational communities, including those who are involved in accelerating the transition of research results into operations. Furthermore, the increasing use of predictions by decision makers throughout federal, state, and local emergency management government agencies and by private/commercial sectors will serve as an important component for this annual meeting along with the extension of predictive capabilities into a broader domain, including public health, food security, air and water quality, alternative energy, and responses to climate trends. Lidar remote sensing is expected to play a significant role in these fields and may even be a key instrument required. Abstracts that address these areas are highly encouraged.

Please submit your abstract electronically via the web by *1 August 2012* (refer to the AMS web page at 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 late-September 2012. 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 6 February 2013. All abstracts, extended abstracts, and presentations will be available on the AMS website at no cost.

For additional information on the organization of the 93rd AMS Annual Meeting, please contact meeting organizers: Belay Demoz (e-mail: bbdemoz@howard.edu) or Sara Tucker (e-mail: stucker@ball.com). (5/12)

CALL FOR PAPERS

Fourth Conference on Environment and Health, 6–10 January 2013, Austin, Texas

The overarching theme for the 2013 AMS Annual Meeting is "Taking Predictions to the Next Level: Expanding Beyond Today's Weather and Climate Forecasts and Projections." Over the past 60 years the meteorological community has made tremendous strides in making prediction a fundamental part of its scientific and operational/service heritage through the development and application of complex numerical models involving the atmosphere, ocean, land, and cryosphere components of the Earth System. Applying our predictive capabilities into a broader domain including public health, food security, air and water quality, alternative energy, and responses to climate trends is a central objective of this meeting.

In the context of this overarching theme, the goal of 4Health is to go in-depth into Earth's influence on human health and well-being. In doing so, we seek to better understand how the atmospheric and oceanic systems exert measurable (positive or negative) impacts; moreover, we are interested in how planetary information feeds into surveillance and preparedness (including adaptation) models and decisions.

We are especially interested in public health and medical factors such as

- asthma
- cardio and respiratory diseases
- foodborne diseases and nutrition
- vectorborne and zoonotic diseases
- waterborne illnesses
- infectious diseases
- mental health
- food securtiy
- heat and extreme weather-related mortality and morbity
- physical safety

The sessions are arranged to help us explore these topics (and possibly others) in the context of hydro-meteorological and oceanographic factors so that our community understands how our science and technologies are utilized (or could be applied) for health. Thus, papers from the environment, health, and medical disciplines that explore this approach through the following subjects are encouraged: integrated modeling; climate, ocean, weather, and water forecasts; in situ and satellite monitoring and observations; communication tools and technologies; and, interdisciplinary coordination.

Of specific interest are papers that address end-to-end science and management approaches of the aforementioned health concerns in the context of these environmental factors:

1) 0cean and coastal–related human health risks
2) dust transport, transformation, and consequence
3) extreme temperatures, including attendant influences on drought and wildfires
4) examples of adaptation risks and solutions at local, regional, and international levels
5) disaster risk reduction for healthcare delivery services (e.g., EMT) and infrastructure (e.g., hospitals), including its systems of dependency (e.g., utility grids, water, sanitation)

Achieving the 4Health goal requires participation and engagement from colleagues in the public health, medical, hydro-meteorological, and oceanic disciplines.

We are considering joint/parallel sessions with the following conferences:

- 29th EIPT/11th Artificial and Computational Intelligence: "Data Mining Techniques for Environment and Health Research" focusing on technological advances that can further environment and health investigations.
- 27th Hydrology: "Drought and Health" to address the impacts that drought (in the United States and overseas) can bear on human health and food security.
- 20th Applied Climatology: "Climate Applications and Projections for the Health Sector" to highlight climate outlooks that can inform public health preparedness, such as areas of increased extreme weather risk, alterations in vector-borne disease trajectories due to weather variability and change, and potential threats to food security.
- 17th IOAS: "Earth Observation Systems and Applications for Public Health Models and Decisions" to focus primarily on satellite applications in a panel discussion that will headlined by keynote talks from both the observations and health communities along with distinguished papers that address current health applications, add value in establishing requirements, highlight untapped data utilization, and discuss techniques (such as data mining) that can expand environment and health exploration and products
- 8Policy/IMPACTS: "Extreme Weather Toll on Mental Health, Safety, and Healthcare Infrastructure" to discuss extreme weather (and outlier events, like 1:1000 or 1:5000 year events) impacts to people and buildings in the healthcare profession. Papers will highlight the discrepancy between preparedness and the probability of extreme or outlier events as covered through several angles: 1) a discussion on critical infrastructure codes, building preparedness, as well as hospital dependencies on energy, utility, and sanitation services; 2) an autopsy of risk perception in the health sector (using Joplin as a test bed); 3) a review of the financial and mental toll resulting from the damage or loss of hospital or healthcare professionals to a community; and 4) international perspectives and experiences in fortifying healthcare infrastructure.

Papers and posters from graduate and undergraduate students are welcome.

For overall questions please contact Sue Estes, NASA (e-mail: sue.m.estes@nasa.gov; tel: 256-961-7961) or Wendy Marie Thomas (e-mail: wthomas@ametsoc.org; tel: 202-355-9820); for extreme temperatures/drought/wildfires topics, Glenn McGregor (e-mail: g.mcgregor@auckland.ac.nz; tel: 64 9 3737599 ext 85280) or Paul English, California Department of Health (e-mail: Paul.English@cdph.ca.gov; tel: 510-620-3684); for health-specific topics please contact Kris Ebi, IPCC/Stanford (e-mail: krisebi@ipcc-wg2.gov) or Paul English, California Department of Health (e-mail: Paul.English@cdph.ca.gov; tel: 510-620-3684); for climate-related topics please contact Eileen Shea, NOAA (e-mail: eileen.shea@noaa.gov; tel: 828-271-4384); for dust-related topics please contact Bill Sprigg, University of Arizona/NASA (e-mail: wsprigg@u.arizona.edu; tel: 520-621-6834); and for oceans and human health topics please contact Juli Trtanj, NOAA (e-mail: juli.trtanj@noaa.gov). (2/12; r5/12)

CALL FOR PAPERS

Second Symposium on Planetary Atmospheres, 6–10 January 2013, Austin, Texas

The Second Symposium on Planetary Atmospheres, sponsored by the American Meteorological Society, will be held 6–10 January 2013, as part of the 93rd AMS Annual Meeting in Austin, Texas. Preliminary programs, registration, hotel, and general information will be posted on the AMS website (www.ametsoc.org/meet/annual/) in late-September 2012.

The theme for the 2013 AMS Annual Meeting is "Taking Predictions to the Next Level: Expanding Beyond Today's Weather and Climate Forecasts and Projections." Over the past 60 years the meteorological community has made tremendous strides in making prediction a fundamental part of its scientific and operational/service heritage through the development and application of complex numerical models involving the atmosphere, ocean, land, and cryosphere components of the Earth System. This theme will serve as a catalyst for the 2013 AMS Annual Meeting by focusing the attention of the research and operational communities, including those who are involved in accelerating the transition of research results into operations. Furthermore, the increasing use of predictions by decision makers throughout federal, state, and local emergency management government agencies and by private/commercial sectors will serve as an important component for this annual meeting along with the extension of predictive capabilities into a broader domain, including public health, food security, air and water quality, alternative energy, and responses to climate trends.

Following this theme, the Second Symposium on Planetary Atmospheres is soliciting papers on advances in spacecraft observations of planetary atmospheres, modeling, and data assimilation. Topics in the areas of planetary meteorology, atmospheric structure, dynamics and composition, and planetary climate are welcomed.

Please submit your abstract electronically via the web by *1 August 2012* (refer to the AMS web page at 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 late-September 2012. 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 6 February 2013. All abstracts, extended abstracts, and presentations will be available on the AMS website at no cost.

For additional information please contact the program chairperson, Mark Richardson (e-mail: mir@ashimaresearch.com). (5/12)

CALL FOR PAPERS

Special Symposium on the Joint Center for Satellite Data Assimilation, 6–10 January 2013, Austin, Texas

The Special Symposium on the Joint Center for Satellite Data Assimilation, sponsored by the American Meteorological Society, and organized by the AMS Satellite Meteorology, Oceanography, and Climatology Committee, will be held on 8 January 2013. The symposium is embedded within the Third Conference on Transition of Research to Operations: Successes, Plans, and Challenges, and is part of the 93rd AMS Annual Meeting in Austin, Texas. Preliminary program, registration, hotel, and general information will be posted on the AMS website (www.ametsoc.org/meet/annual/) in late-September 2012.

The theme for the 2013 AMS Annual Meeting is "Taking Predictions to the Next Level: Expanding Beyond Today's Weather and Climate Forecasts and Projections." Over the past 60 years the meteorological community has made tremendous strides in making prediction a fundamental part of its scientific and operational/service heritage through the development and application of complex numerical models involving the atmosphere, ocean, land, and cryosphere components of the Earth System.

Much of this progress has been made possible by the development of better data assimilation systems that in turn have made it possible for the operational prediction centers to increase and improve their use of a wider range of observing systems. For certain application areas—especially numerical weather prediction—the increased use of satellite data has been a critical element of this overall thrust since comprehensive spatial and temporal coverage of weather data for the full global domain can only be obtained from space.

The Joint Center for Satellite Data Assimilation is an interagency collaboration sponsored by NASA, NOAA, the U.S. Air Force, and the U.S. Navy that is tasked with improving and accelerating the use of satellite data and related research in operational environmental prediction systems. As one of its primary responsibilities, the JCSDA strives to help the operational agencies implement data from new satellites as quickly as possible after launch. Thus, the JCSDA helps the nation maximize the benefits from its investment in these systems. The symposium will include both invited and contributed presentations and we solicit presentations highlighting the role of satellite data in numerical weather prediction, as well as on the current and potential future use of satellite data in air quality, ocean, land surface, and climate prediction systems. Contributions may focus on the data themselves or on algorithmic developments that are/will be necessary to optimize the use of the data.

Please submit your abstract electronically via the web by *1 August 2012* (refer to the AMS web page at 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 late-September 2012. 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 6 February 2013. All abstracts, extended abstracts, and presentations will be available on the AMS website at no cost.

For additional information please contact the program chairperson, Lars Peter Riishojgaard (e-mail: Lars.P.Riishojgaard@nasa.gov). (5/12)

CALL FOR PAPERS

Symposium on the Role of Statistical Methods in Weather and Climate Prediction, 6–10 January 2013, Austin, Texas

The Symposium on the Role of Statistical Methods in Weather and Climate Prediction, sponsored by the American Meteorological Society, and organized by the AMS Committee on Probability and Statistics, will be held on 10 January 2013, as part of the 93rd AMS Annual Meeting in Austin, Texas. Preliminary programs, registration, hotel, and general information will be posted on the AMS website (www.ametsoc.org/meet/annual/) in late-September 2012.

The theme for the 2013 AMS Annual Meeting is "Taking Predictions to the Next Level: Expanding Beyond Today's Weather and Climate Forecasts and Projections." Over the past 60 years the meteorological community has made tremendous strides in making prediction a fundamental part of its scientific and operational/service heritage through the development and application of complex numerical models involving the atmosphere, ocean, land, and cryosphere components of the Earth System. This theme will serve as a catalyst for the 2013 AMS Annual Meeting by focusing the attention of the research and operational communities, including those who are involved in accelerating the transition of research results into operations. Furthermore, the increasing use of predictions by decision makers throughout federal, state, and local emergency management government agencies and by private/commercial sectors will serve as an important component for this annual meeting along with the extension of predictive capabilities into a broader domain, including public health, food security, air and water quality, alternative energy, and responses to climate trends.

Following this theme, this symposium is soliciting papers on the role of statistical and probabilistic methods in the prediction systems for weather, climate, and user variables (e.g., hydrologic prediction). In addition to papers focused on methodologies and advances in capabilities, some talks on user "best practices" are also solicited. A number of invited talks will provide overviews of the state-of-the-art of research and best practices and some specific discussions will focus on advances in these areas. A poster session will be included to allow greater participation in the symposium. The symposium is also planning to convene joint sessions with the Hydrology, Climate Variability and Change, Artificial Intelligence, and Planned and Inadvertent Weather Modification Committees, so presentations that concern the crossover of statistical and probabilistic methods with these topic areas are also invited.

Please submit your abstract electronically via the web by *1 August 2012* (refer to the AMS web page at 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 late-September 2012. 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 6 February 2013. All abstracts, extended abstracts, and presentations will be available on the AMS website at no cost.

For additional information please contact the program chairpersons, Barbara Brown (e-mail: bgb@ucar.edu), Dan Collins (e-mail: dan.collins@noaa.gov), Bob Glahn (e-mail: harry.glahn@noaa.gov), and Scott Sellars (e-mail: scott.sellars@uci.edu). (5/12)

NOMINATION SUBMISSIONS

The Council of the American Meteorological Society invites members of the AMS to submit nominations for the Society Awards, Lecturers, Named Symposia, Fellows, Honorary members, and nominees for elective Officers and Councilors of the Society.

Information regarding awards, including award descriptions, listings of previous recipients, and the process for submitting nominations are on the AMS website www.ametsoc.org/awards.

Note: Deadlines differ and some nominations must be submitted on a specific form vs. electronic submission which is available on the AMS website or by request from Headquarters.

2013 AWARDS COMMITTEES

Each committee or commission listed below has the responsibility to select and submit to the Council the names of individuals nominated for the Society's awards listed. The name(s) of individual(s) nominated, a two-page cv, a bibliography of no more than three pages, and three supporting letters should be electronically submitted before **1 May 2013** for the awards that follow, unless stated otherwise. The nominees for awards remain on the committee's active list for three years.

ATMOSPHERIC RESEARCH AWARDS COMMITTEE

The Carl-Gustaf Rossby Research Medal
The Jule G. Charney Award
The Verner E. Suomi Award*
The Remote Sensing Prize (biennial)
The Clarence Leroy Meisinger Award
The Henry G. Houghton Award

OCEANOGRAPHIC RESEARCH AWARDS COMMITTEE

The Sverdrup Gold Medal
The Henry Stommel Research Award
The Verner E. Suomi Award*
The Nicholas P. Fofonoff Award

AWARDS OVERSIGHT COMMITTEE

The Charles Franklin Brooks Award for Outstanding Services to the Society
The Cleveland Abbe Award for Distinguished Service to the Atmospheric Sciences by an Individual
The Joanne Simpson Mentorship Award
The Award for Outstanding Services to Meteorology by a Corporation
Special Awards

EDUCATION AND HUMAN RESOURCES COMMISSION

The Louis J. Battan Author's Award (Adult and K–12)
The Charles E. Anderson Award
The Teaching Excellence Award
Distinguished Science Journalism in the Atmospheric and Related Sciences

PROFESSIONAL AFFAIRS COMMISSION

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

WEATHER AND CLIMATE ENTERPRISE COMMISSION

The Kenneth C. Spengler Award

LOCAL CHAPTER AFFAIRS COMMITTEE

Local Chapter of the Year Award
(nomination form available online at www.ametsoc.org/amschaps/index.html.)

* Recommended by the Atmospheric Research Awards Committee in even-numbered years and by the Oceanographic Research Awards Committee in odd-numbered years.

2012 AWARDS COMMITTEES

SCIENTIFIC AND TECHNOLOGICAL ACTIVITIES COMMISSION

The Charles L. Mitchell Award
The Award for Exceptional Specific Prediction
The Francis W. Reichelderfer Award
The Helmut E. Landsberg Award
The Award for Outstanding Achievement in Biometeorology

- **LECTURERS** *(Deadline: 1 October 2012)*
  Robert E. Horton Lecturer in Hydrology
  Bernhard Haurwitz Memorial Lecturer
  Walter Orr Roberts Lecturer

- **STUDENT PAPERS**
  Robert Leviton
  Banner I. Miller
  Max A. Eaton Prize
  Spiros G. Geotis Prize
  Peter V. Hobbs Student Prize

- **NAMED SYMPOSIA**
  Section E, of the Policy, Guidelines, and Procedures for Awards and Lectureships provides the Policy on Named Conferences/Symposia and Special Issues of AMS Journals *(full policy description available at www.ametsoc.org/awards):*

> Recognition of scientists in the fields served by the AMS, living or deceased, in the form of a named conference or symposium or a named special issue of one of the Society's journals is an honor reserved for only the most outstanding of our colleagues. It should be awarded only to those individuals who are completing a career, or who have recently died having completed a career, of significant achievements in their field and whose contributions would make them worthy of consideration for Honorary Member of the AMS…

2013 FELLOWS COMMITTEE

The Committee's function is to submit to the Council the names of individuals for election to Fellow.

> Article III, Section 6, of the AMS Constitution provides that those eligible for election to Fellow shall have made outstanding contributions to the atmospheric or related oceanic or hydrologic sciences or their applications during a substantial period of years. The nominees for Fellow must be a member of the Society and remain on the committee's active list for three years.

A nomination letter and three supporting letters should be electronically submitted before 1 May 2013. A list of Fellows and the process for submitting nominations are on the AMS website (www.ametsoc.org/awards).

2013 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 94th Annual Meeting (January 2014) and 2) four positions on the Council for a term of three-years starting at the close of the Annual Meeting. Nominations must be submitted prior to 1 April 2013 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 2012; a form and list of Honorary Members is available at www.ametsoc.org/awards.

CORPORATION AND INSTITUTIONAL MEMBERS

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

SUSTAINING MEMBERS

Ball Aerospace & Technologies Corporation
Harris Corporation
ITT Exelis
Lockheed Martin Corporation
Northrop Grumman Corporation
The Boeing Company
University Corporation for Atmospheric Research
Vaisala, Inc.

REGULAR MEMBERS

3TIER Environmental Forecast Group, Inc.
AccuWeather, Inc.
ADNET Systems, Inc.
Aerospace & Marine International Corporation
AirDat LLC
All Weather, Inc.
Atmospheric and Environmental Research, Inc.
Atmospheric Technology Services Company, LLC
AWS Truepower, LLC
Baron Services, Inc.
Belfort Instrument Company
Botswana Meteorological Services
Bristol Industrial & Research Associates Ltd (BIRAL)
Campbell Scientific, Inc.
Climatronics Corporation
CLS America, Inc.
Coastal Environmental Systems
Computer Sciences Corporation
CSIRO Marine and Atmospheric Research
Davis Instruments Corporation
DeTect, Inc.
EKO Instruments Company, Ltd.
Enterprise Electronics Corporation
Environmental Systems Research, Inc.
EWR Weather Radar Systems
Florida State University, Department of EOAS
Geophysical Institute/International Arctic Research Center
Global Hydrology and Climate Center
I. M. Systems Group
IPS MeteoStar
Jenoptik I Defense & Civil Systems
Johns Hopkins University, Applied Physics Laboratory
Kipp & Zonen USA Inc.
Met One Instruments, Inc.
Meteorological Technology International
MeteoSwiss
Murray & Trettel, Inc.
National Centre for Medium Range Weather Forecasting
Naval Meteorology and Oceanography Command
Noblis, Inc.
Orbital Sciences Corporation
Pelmorex Media Inc.
R. M. Young Company
Radiometrics Corporation
Raytheon Company
Riverside Technology, inc.
Royal Netherlands Meteorological Institute
Scintec AG
SeaSpace Corporation
SGT, Inc.
SigmaSpace Corporation
Sonalysts, Inc.
SpectraSensors, Inc.
Sutron Corporation
Telvent DTN
The Climate Corporation
The Weather Channel
U.S Department of Energy, Office of Science
Unisys Corporation
University of Alabama in Huntsville,Earth System Science Ctr
University of Wisconsin - Madison, SSEC
Weather Central, LP
Weather Decision Technologies
Weather Modification, Inc.
Weather Services International, Inc.
WindLogics, Inc.
Wyle

SMALL BUSINESS MEMBERS

Atmospheric Systems Corporation
Climadata Corporation
Geonor, Inc.
National Council of Industrial Meteorologists
National Weather Service Employees Organization
Remtech, Inc.
Sky Power International, LLC
The Beautiful Weather Corporation
www.WeatherVideoHD.TV
Yankee Environment Systems, Inc.

PUBLICATIONS MEMBERS

Abdus Salam International Centre for Theoretical Physics
Air Force Weather Agency

For questions relating to corporation and institutional membership, please contact Gary Rasmussen at AMS Headquarters—telephone: 617-227-2426, x3981; fax: 617-742-8718; e-mail: grasmussen@ametsoc.org; or write to American Meteorological Society, Attn: Dr. R. Gary Rasmussen, 45 Beacon St., Boston, MA 02108-3693.

CORPORATION AND INSTITUTIONAL MEMBERS

Bureau of Meteorology
Civil Aeronautics Administration, MOTC
Colorado State University Libraries
Columbia University, Lahmont-Doherty Geological Observatory
Creighton University Reinert/Alumni Memorial Library
Dartmouth College Baker Library
Desert Research Institute
Deutscher Wetterdienst
Embry Riddle Aeronautical University
Environment Canada Library, Downsview
EUMETSAT Library
Finnish Meteorological Institute
Florida International University Library
Harvard University, Gordon McKay and Blue Hill Libraries
Hong Kong Observatory Library
Indian Institute of Tropical Meteorology
Indiana University Library
Institute of Global Environment and Society Library
Irish Meteorological Service
Japan Weather Association
Los Alamos National Laboratory
Lyndon State College, Samuel Read Hall Library
Maryland Department of the Environment
MBL/WHOI Library
Meteo-France
Meteorological Service of New Zealand Ltd.
Meteorologisk institutt
Millersville University, Department of Earth Sciences
MIT, Lincoln Laboratory
National Weather Center Library
Naval Postgraduate School, Dudley Knox Library
New York University
Niedersachsische Staats
NIWA Wellington Library
NOAA AOML Library
NOAA Central Library
NOAA – GLERL Library
NOAA National Climatic Data Center
NOAA Seattle Library
North Carolina State University Libraries
Pennsylvania State University, Paterno Library
Purdue University Libraries
Republic of Korea Air Force, Headquarters
South African Weather Service
St. Louis University, Dept. of Earth & Atmospheric Sciences
Swedish Meteorological & Hydrological Institute
U.K. National Meteorological Library
U.S Air Force, 335 TRS/UOAA
U.S. Army Corps of Engineers, Library - ERDC
U.S. Department of Commerce, Boulder Labs Library
U.S. EPA Main Library
U.S. Naval Maritime Forecast Center
Universitatsbibliothek Innsbruck
Universitatsbibliothek Trier
Universite de Versailles
University of Colorado Libraries
University of Copenhagen, Niels Bohr Institute Library
University of Delaware Library
University of Frankfurt Library
University of Hawaii at Manoa, Library
University of Maryland, McKeldin Library
University of Melbourne, Baillieu Library
University of New South Wales Library
University of North Carolina, Ramsey Library
University of North Dakota, Chester Fritz Library
University of Northern Colorado, Michener Library
University of Oklahoma, School of Meteorology
University of Quebec at Montreal
University of Rhode Island, Pell Marine Science Library
University of Washington Libraries
WeatherPredict Consulting Inc.
Weizmann Institute of Science
Yale University, Geology Library
Zentralanstalt fur Meteorologie und Geodynamik

Color indicates new or reinstated member

FELLOWSHIP AND SCHOLARSHIP SPONSORS

FELLOWSHIPS

AMS 21st Century Campaign
ITT*
Lockheed Martin Corporation*
NASA's Earth Science Enterprise
NOAA's National Weather Service
NOAA's Climate Program Office
SAIC, Earth Sciences Operation

FRESHMAN AND UNDERGRADUATE SCHOLARSHIPS

Baron Radar Services
Baron Advanced Meteorological Systems
CLS America, Inc.
Earth Networks
Harris Corporation
Lockheed Martin MS2
NOAA's Office of the Federal Coordinator for Meteorology
Raytheon Information Services
Riverside Technologies, inc.
R. M. Young Company
Science and Technology Corporation
Vaisala, Inc.
Jerome Namias Memorial Endowed Scholarship
Edgar J. Saltsman Endowed Scholarship
Bernard Vonnegut and Vincent Schaefer Endowed Scholarship
Percival D. Wark and Clara B. (Mackey) Wark Endowed Scholarship

MINORITY SCHOLARSHIPS

AMS 21st Century Campaign
Baron Services
Earth Resources Technology, Inc.

SENIOR SCHOLARSHIPS

AMS 75th Anniversary Endowed Scholarship
Bhanwar Lal Bahethi Scholarship
Om and Saraswati Bahethi Scholarship
Saraswati (Sara) Bahethi Scholarship
Werner A. Baum Undergraduate Endowed Scholarship
Loren W. Crow Memorial Scholarship
Karen Hauschild Friday Endowed Scholarship
Bob Glahn Endowed Scholarship in Statistical Meteorology
Dr. Pedro Grau Undergraduate Scholarship
Richard and Helen Hagemeyer Scholarship
John R. Hope Endowed Scholarship in Atmospheric Sciences
David S. Johnson Endowed Scholarship
Larry R. Johnson Scholarship
Dr. Yoram Kaufman Scholarship
Carl W. Kreitzberg Endowed Scholarship
Max Mayfield Scholarship in Weather Forecasting
Ethan and Allan Murphy Endowed Memorial Scholarship
K. Vic Ooyama Endowed Scholarship
Howard T. Orville Endowed Scholarship in Meteorology
Guillermo Salazar Rodriguez Undergraduate Scholarship
Mark J. Schroeder Endowed Scholarship in Meteorology

*Corporate Patron

SPACE RESERVED FOR CERTIFIED CONSULTING METEOROLOGISTS

Certified Consulting Meteorologist: The certification program of the American Meteorological Society is aimed at fostering the establishment and maintenance of a high level of professional competency, and mature and ethical counsel, in the field of consulting meteorology. Requirements of knowledge, experience, and character are determined by a five-person board. Objectives of the program and application procedures are described in full detail in the August 2001 *Bulletin* (pp. 1689–1694).

PROFESSIONAL DIRECTORY

SPACE RESERVED FOR CERTIFIED CONSULTING METEOROLOGISTS

Certified Consulting Meteorologist: The certification program of the American Meteorological Society is aimed at fostering the establishment and maintenance of a high level of professional competency, and mature and ethical counsel, in the field of consulting meteorology. Requirements of knowledge, experience, and character are determined by a five-person board. Objectives of the program and application procedures are described in full detail in the August 2001 *Bulletin* (pp. 1689–1694).

PROFESSIONAL DIRECTORY

SPACE RESERVED FOR MEMBERS

SPACE RESERVED FOR MEMBERS

For professional card rates, please apply to:
Executive Director, American Meteorological Society, 45 Beacon St., Boston, MA 02108-3693

INDEX TO ADVERTISERS

ONLINE CAREER CENTER

The AMS Online Career Center may be accessed through the AMS Web site at www.ametsoc.org/careercenter/index.html. In addition to posting positions, advertisers may search and view job seekers' résumés.

Job Posting Rates:
$375 (30-day posting)

$1593.75 (5 pack of jobs) Usable for 30-day job postings. Buy 5 job posting credits at a 15% discounted rate. These credits may be used at anytime during the next 12 months.

$3000 (10 pack of jobs) Usable for 30-day job postings. Buy 10 job-posting credits at a 20% discounted rate. These credits may be used at anytime during the next 12 months.

$3375 (12 pack of jobs) Usable for 30-day job postings or a continual 12-month posting. Buy 12 job-posting credits at a 25% discounted rate. These credits may be used at anytime during the next 12 months.

Advertisers may upload a company logo free of charge.

Résumés: View complete resumes for free! If you find any candidates you are interested in, submit your interest to them. If the candidate is interested in your opportunity, we connect you for just $20.00. If the candidate is not interested, you pay nothing!

AMS Corporation Member Discounts: Active AMS Corporation Members (small business, regular, or sustaining) receive a 25% discount when posting a position. Contact Kelly G. Savoie (ksavoie@ametsoc.org) to receive a coupon code. To receive the discount, the code must be entered when you post a position. The discount code is non-transferable.

AMS Member Benefit: AMS Members will be given 14-days advance access to a job listing. A member-only symbol will appear next to the posting. After 14 days, the job posting is open to all.

Submission of Ads: Advertisers must create an online account and submit ad text through the AMS Career Center site. Ad text may be entered at any time.

Payment Information: Prepayment is required by credit card or valid purchase order.

Contact Information: If you have questions, please contact Customer Service at 888-575-WORK (9675) (inside U.S.) or 860-440-0635 (outside U.S.).

ADVERTISING POLICY

The AMS will accept tasteful and accurate advertisements for products and services of professional interest to AMS members from organizations that are actively involved in the atmospheric and related sciences. The AMS also accepts advertising from organizations that have an interest in the atmospheric and related sciences and services, but are not actively involved in them. These organizations may promote their contributions to AMS activities and other good works, but may not directly promote products or services. The AMS reserves the right to refuse advertising that does not meet these criteria. Acceptance of advertising does not constitute the Society's endorsement of the product or service being advertised.

ORDER FORM

FOR AMS PUBLICATIONS ADVERTISED IN THIS ISSUE

Name: ______________________________________ ☐ Member (# __________)

Address: ____________________________________ ☐ Nonmember

City, State: __________________________ ZIP: __________

Province: _______________ Country: __________________

	Qty.	Member Price*	Nonmember Price*	Total
		(Please circle appropriate price)		
The AMS Weather Book: The Ultimate Guide				
to America's Weather (p. 610)		$25.00	$35.00	
Deadly Season: Analysis of the 2011 Tornado Outbreaks (p. 590)		$20.00	$25.00	
Economic and Societal Impacts of Tornadoes (p. 736)		$22.00	$30.00	
The Forgiving Air (p. 668)		$16.00	$22.00	
Student member price:		$35.00		
Glossary of Meteorology, Second Edition (p. 630)		$60.00	$85.00	
Student member price:		$35.00		
Glossary of Meteorology, Second Edition (CD ROM; p. 630)		$65.00	$95.00	
Glossary of Weather and Climate (p. 651) **Softcover:**		$21.00	$26.95	
Hardcover:		$34.95	$34.95	
A Half Century of Progress in Meteorology:				
A Tribute to Richard Reed, MM No. 53 (p. 758)		$60.00	$80.00	
Midlatitude Synoptic Meteorology (p. 629)		$75.00	$100.00	
Student member price:		$65.00		
Student member price:		$75.00		
Radar and Atmospheric Science: A Collection of Essays				
in Honor of David Atlas (p. 747)		$80.00	$100.00	
Severe Convective Storms, MM No. 50 (p. 734)		$90.00	$110.00	
Weather on the Air: A History of Broadcast Meteorology (p. 686)		$25.00	$35.00	
**** Shipping and handling: Please add $8 PER ORDER for delivery within the U.S. and $15 PER ITEM for deliveries outside the U.S. There is no shipping and handling charge on DVDs or CD-ROMs for either U.S. or foreign orders. Shipping prices subject to change.***		**SHIPPING**		
		TOTAL		

I am paying by: ☐ Check/money order ☐ Credit Card No. ______________________ Exp. date:_____

☐ Visa ☐ Mastercard ☐ American Express

Name on Card:_________________________ Billing address: _________________________

Signature: ___________________________ _________________________

☐ Please include an AMS membership application with my order. _________________________

Please send prepaid orders to: Order Department, American Meteorological Society, 45 Beacon St., Boston, MA 02108-3693