Volume 92 Number 12 December 2011

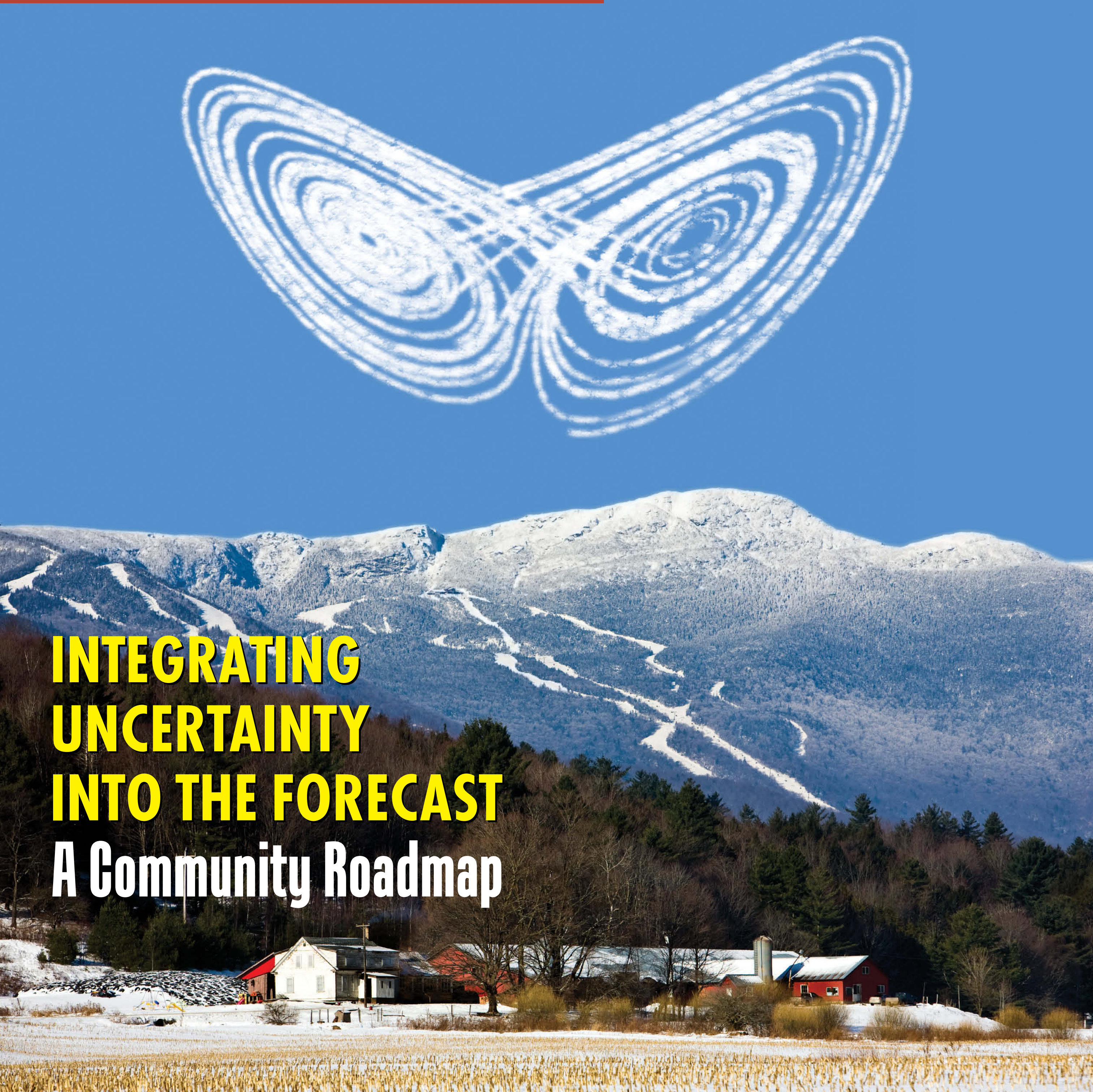
BAMS

Bulletin of the American Meteorological Society

QUALITY ASSURANCE FOR MODELS

METEOROLOGY OVER SMALL HILLS

ICE NUCLEI MEASUREMENTS



INTEGRATING UNCERTAINTY INTO THE FORECAST

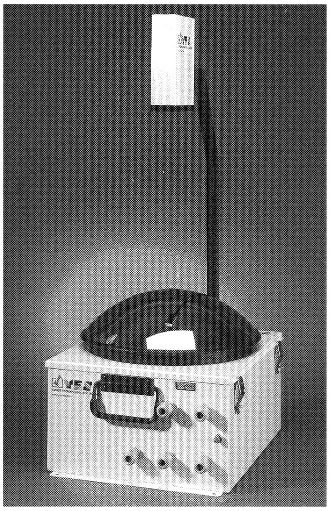
A Community Roadmap


SOLYS 2


Large Aperture Scintillometer

ATMOSPHERIC RADIATION INSTRUMENTATION

☑ TOTAL SKY IMAGERS



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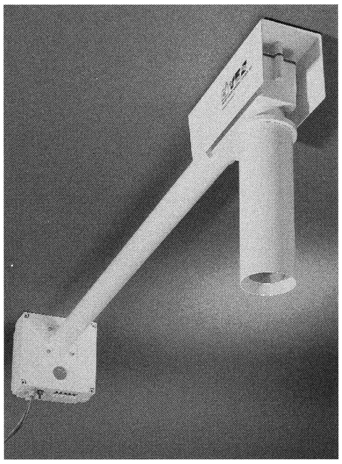

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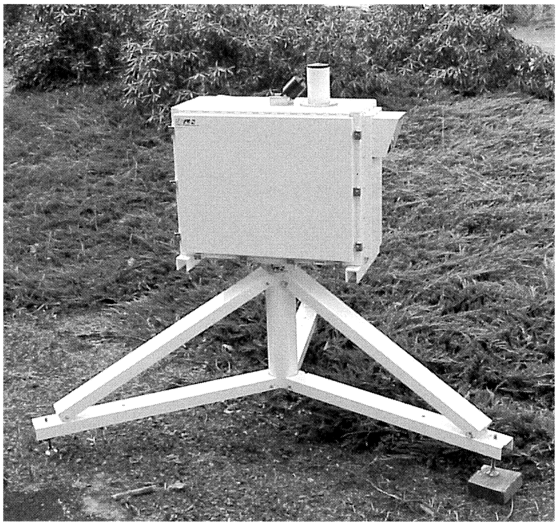

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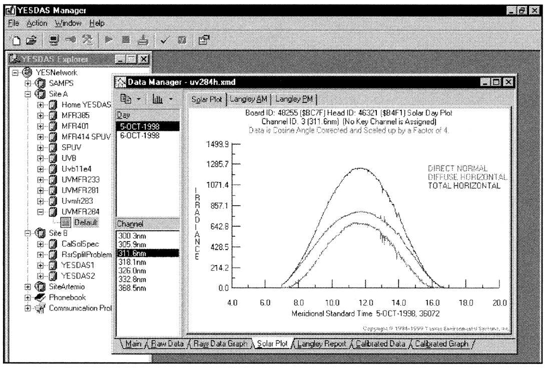

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Instruments that measure up↑

BAMS
Bulletin of the American Meteorological Society

VOLUME 92, NUMBER 12, DECEMBER 2011

IN BOX

ESSAY

ARTICLES

FORUM

COMMENTS

ON THE COVER

Starting with recent recommendations from the WMO, National Research Council, and AMS itself, an AMS Committee has established strategic goals and an implementation plan for the weather and climate community to achieve routine, comprehensive, reliable, and useful uncertainty information in its forecasts. For further details, see Hirschberg et al., beginning on page 1651.

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CONTENTS

NOWCAST

45 BEACON

THE FRONT PAGE

RECENT HEADLINES ON THE AMS BLOG

Plane Has Combative Attitude toward Storms

A Slam-Dunk Choice for a Gift This Season

iPhone Game Puts Satellite Data in Your Hands

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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.

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LETTER FROM THE EDITOR: CERTAIN LESSONS ABOUT SCIENCE

In eighth grade—at last!—my school offered a lab class. The idea was to teach the scientific method. However, mastery of simple tasks like heating up the contents of a test tube and weighing the result eluded us newbies. The results seemed hopelessly variable—from one student to another, not to mention compared to the textbooks.

We did what, I think, most people fearful of uncertainty and bad grades would do. We adjusted our outliers to provide more "realistic" data. We were so uncertain about our abilities we nudged the numbers toward the "right" answers.

In real world science, not just in a middle school lab course gone awry, it is possible for uncertainties to overwhelm data. DeMott et al. tell such a story in this issue. For years in situ observations of ice nuclei were so unbelievable that they were mostly shelved in favor of modeling studies. Only with recent technological and analytical developments, coupled with new urgency to gather information, have scientists focused again on observing in the field.

Scan this to watch a video of Paul DeMott discussing his article, or go to http://youtu.be/eWlajEKbt_A.

However, this is an exceptional story. The lesson we mistakenly reinforced in eighth grade science was that there are right answers and wrong answers. We lost an opportunity to learn how science works—about how uncertainty does not stop scientists from observing and making conclusions. Science analyzes, not discards, uncertainties.

This is a critical lesson. Ever since Laplace, scientists have been able to assess results about the unknown—to quantify and predict the value of the information they gather. Lacking a grasp of this statistical toolbox, such uncertainty makes people uncomfortable. How many of us intuitively realize that the odds are 50/50 that two people in a room of 23 will share a birthdate?

But this doesn't mean we need to be pessimistic about communicating uncertainty to policymakers, emergency managers, and other customers of scientific information, which is a goal shared by Hirschberg et al., Curry and Webster, and Hegerl et al. in this issue. The mathematics of probabilities and unknowns are invisible to most people, but they are not foreign to the way all humans think. Silently, they shape our choices. We switch lanes on the freeway, taking risks in hopes of improving our journey. We check bags at the airport not knowing if they'll get where we're going. We second-guess the decisions teams make to attempt 50-yard field goals, to bunt with bases loaded, and to foul jump shooters.

It is often said we need to embrace uncertainty in science. Not just to be honest with the public, and not just to teach them how science works—instead just to be a natural part of daily conversation. Uncertainty is what we all deal with every day, newbies and Nobelists alike.

—*Jeff Rosenfeld,* Editor-in-Chief

ABSTRACTS

QUALITY ASSURANCE IN ATMOSPHERIC MODELING

This paper summarizes a number of best practices associated with the use of numerical models of the atmosphere and is motivated by the rapid growth in the number of model users, who have a range of scientific and technical preparations. An underlying important message is that models are complex and imperfect tools, and model users must be aware of their strengths and weaknesses and be thorough in the process of model configuration and verification. *(Page 1601)*

CUSTOMIZED SPATIAL CLIMATE MODELS FOR NORTH AMERICA

Over the past two decades, researchers at Natural Resources Canada's Canadian Forest Service, in collaboration with the Australian National University (ANU), Environment Canada (EC), and the National Oceanic and Atmospheric Administration (NOAA), have made a concerted effort to produce spatial climate products (i.e., spatial models and grids) covering both Canada and the United States for a wide variety of climate variables and time steps (from monthly to daily), and across a range of spatial resolutions. Here we outline the method used to generate the spatial models, detail the array of products available and how they may be accessed, briefly describe some of the usage and impact of the models, and discuss anticipated further developments. Our initial motivation in developing these models was to support forestry-related applications. They have since been utilized by a wider range of agencies and researchers. This article is intended to further raise awareness of the strengths and weaknesses of these climate models and to facilitate their wider application. *(Page 1611)*

RESURGENCE IN ICE NUCLEI MEASUREMENT RESEARCH

Understanding cloud and precipitation responses to variations in atmospheric aerosols remains an important research topic for improving the prediction of climate. Knowledge is most uncertain, and the potential impact on climate is largest with regard to how aerosols impact ice formation in clouds. In this paper, we show that research on atmospheric ice nucleation, including the development of new measurement systems, is occurring at a renewed and historically unparalleled level. A historical perspective is provided on the methods and challenges of measuring ice nuclei, and the various factors that led to a lull in research efforts during a nearly 20-yr period centered about 30 yr ago. Workshops played a major role in defining critical needs for improving measurements at that time and helped to guide renewed efforts. Workshops were recently revived for evaluating present research progress. We argue that encouraging progress has been made in the consistency of measurements using the present generation of ice nucleation instruments. Through comparison to laboratory cloud simulations, these ice nuclei measurements have provided increased confidence in our ability to quantify primary ice formation by atmospheric aerosols. *(Page 1623)*

COLPEX: FIELD AND NUMERICAL STUDIES OVER A REGION OF SMALL HILLS.

During stable nighttime periods, large variations in temperature and visibility often occur over short distances in regions of only moderate topography. These are of great practical significance and yet pose major forecasting challenges because of a lack of detailed understanding of the processes involved and because crucial topographic variations are often not resolved in current forecast models. This paper describes a field and numerical modeling campaign, Cold-Air Pooling Experiment (COLPEX), which addresses many of the issues.

The observational campaign was run for 15 months in Shropshire, United Kingdom, in a region of small hills and valleys with typical ridge–valley heights of 75–150 m and valley widths of 1–3 km. The instrumentation consisted of three sites with instrumented flux towers, a Doppler lidar, and a network of 30 simpler meteorological stations. Further instrumentation was deployed during intensive observation periods including radiosonde launches from two sites, a cloud droplet probe, aerosol monitoring equipment, and an instrumented car. Some initial results from the observations are presented illustrating the range of conditions encountered.

The modeling phase of COLPEX includes use of the Met Office Unified Model at 100-m resolution, and some brief results for a simulation of an intensive observation period are presented showing the model capturing a cold-pool event. As well as aiding interpretation of the observations, results from this study are expected to inform the design of future generations of operational forecasting systems *(Page 1636)*

A WEATHER AND CLIMATE ENTERPRISE STRATEGIC IMPLEMENTATION PLAN FOR GENERATING AND COMMUNICATING FORECAST UNCERTAINTY INFORMATION

The American Meteorological Society (AMS) Weather and Climate Enterprise Strategic Implementation Plan for Generating and Communicating Forecast Uncertainty (the Plan) is summarized. The Plan (available on the AMS website at www.ametsoc.org/boardpges/cwce/docs/BEC/ACUF/2011-02-20-ACUF-Final-Report.pdf) is based on and intended to provide a foundation for implementing recent recommendations regarding forecast uncertainty by the National Research Council (NRC), AMS, and World Meteorological Organization. It defines a vision, strategic goals, roles and respon-

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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*.

ABSTRACTS

sibilities, and an implementation road map to guide the weather and climate enterprise (the Enterprise) toward routinely providing the nation with comprehensive, skillful, reliable, and useful information about the uncertainty of weather, water, and climate (hydrometeorological) forecasts. Examples are provided describing how hydrometeorological forecast uncertainty information can improve decisions and outcomes in various socioeconomic areas. The implementation road map defines objectives and tasks that the four sectors comprising the Enterprise (i.e., government, industry, academia, and nongovernmental organizations) should work on in partnership to meet four key, interrelated strategic goals: 1) understand social and physical science aspects of forecast uncertainty; 2) communicate forecast uncertainty information effectively and collaborate with users to assist them in their decision making; 3) generate forecast uncertainty data, products, services, and information; and 4) enable research, development, and operations with necessary information technology and other infrastructure. The Plan endorses the NRC recommendation that the National Oceanic and Atmospheric Administration and, in particular, the National Weather Service, should take the lead in motivating and organizing Enterprise resources and expertise in order to reach the Plan's vision and goals and shift the nation successfully toward a greater understanding and use of forecast uncertainty in decision making. *(Page 1651)*

CLIMATE SCIENCE AND THE UNCERTAINTY MONSTER

How to understand and reason about uncertainty in climate science is a topic that is receiving increasing attention in both the scientific and philosophical literature. This paper provides a perspective on exploring ways to understand, assess, and reason about uncertainty in climate science, including application to the Intergovernmental Panel on Climate Change (IPCC) assessment reports. Uncertainty associated with climate science and the science–policy interface presents unique challenges owing to the complexity of the climate system itself, the potential for adverse socioeconomic impacts of climate change, and the politicization of proposed policies to reduce societal vulnerability to climate change. The challenges to handling uncertainty at the science–policy interface are framed using the "monster" metaphor, whereby attempts to tame the monster are described. An uncertainty lexicon is provided that describes the natures and levels of uncertainty and ways of representing and reasoning about uncertainty. Uncertainty of climate models is interpreted in the context of model inadequacy, uncertainty in model parameter values, and initial condition uncertainty. This article examines the challenges of building confidence in climate models and, in particular, the issue of confidence in simulations of the twenty-first-century climate. The treatment of uncertainty in the IPCC assessment reports is examined, including the IPCC Fourth Assessment Report conclusion regarding the attribution of climate change in the latter half of the twentieth century. Ideas for monster-taming strategies are discussed for institutions, individual scientists, and communities. *(Page 1667)*

LETTER TO THE EDITOR

Fixing the Book Review

My book, *Fixing the Sky: The Checkered History of Weather and Climate Control* (Columbia University Press, 2010), received an odd review in *BAMS* this month, basically warning meteorologists to steer clear of it. I would like your readers to know that the reviewer may have a conflict of interest, since his proposal to control hurricanes using chaos theory is part of this checkered history and is mentioned in the book on pages 18, 85, and 230, and is covered on pages 196–198.

Fixing the Sky is a prize-winning book. It was just awarded the AMS Louis J. Battan Author's Award, an Atmospheric Science Librarians International ASLI Choice Award, and the Sally Hacker Prize from the Society for the History of Technology for the best book in the history of technology directed to a broad audience of readers, including students and the interested public.

James Rodger Fleming
Colby College
Waterville, Maine

Editor's Note: The original version of the review of *Fixing the Sky* included a disclosure by the reviewer stating that his work was criticized in the book. This disclosure was inadvertently left out of the final version of the review. *BAMS* regrets the error.

NOWCAST

NEWS AND NOTES

NEW ICELANDIC CURRENT MAY INFLUENCE CLIMATE

The Atlantic Meridional Overturning Circulation (AMOC), a vital part of Earth's ocean conveyor belt, delivers warm water to high latitudes and cooler water to the equator, significantly influencing global climate by transporting large amounts of heat in the process. A recent study of a newly discovered current off the northern coast of Iceland has introduced an alternate explanation for the source and movement of the southbound flow of the AMOC, which in turn could help to advance research on climate and air–sea interactions.

An important piece of the circulation process is the Denmark Strait Overflow Water (DSOW), a large plume of cold, dense water (known as "overflow") that funnels through gaps in the Greenland–Scotland Ridge—which divides the North Atlantic and the Norwegian Sea—and on to the AMOC. It has commonly been believed that the East Greenland Current, off Greenland's eastern coast, feeds the DSOW. But in 2004, Icelandic oceanographers observed a previously undiscovered deep current along the continental slope of Iceland that represented a new potential source current flowing into the AMOC. Over time, they confirmed its existence and named the south-flowing current the North Icelandic Jet (NIJ). More recently, a study published in the online version of *Nature Geoscience*, used a numerical model to examine where and how the NIJ formed and whether it feeds the DSOW.

Their research showed that NIJ contributes "approximately half of the total overflow transport [in the DSOW] and nearly all of the densest component," according to study coauthor Robert Pickart of the Woods Hole Oceanographic Institution. It was also found that the NIJ forms as a result of the warm, salty water from the northward-flowing North Icelandic Irminger Current losing its heat to the Arctic and forming a reservoir of cooler, denser water in the Iceland Sea; this cool water then sinks and starts moving southward as a new current.

The finding calls into question many fundamental beliefs about the AMOC and its relation to climate.

"We've identified a new paradigm," says Pickart. "If a large fraction of the overflow water comes from the NIJ, then we need to rethink how quickly the warm-to-cold conversion of the AMOC occurs," and, more broadly, how this process is connected to climate, he says.

The researchers hope to gain more insight on the origins of the NIJ with additional research that will continue through the summer of 2012. More on their work can be found at www.whoi.edu/denmarkstrait/home. (SOURCE: National Science Foundation)

MICROBES GOING MOBILE

For microbial particles, when it comes to traveling, it's better to be a Volkswagen Bug than an 18-wheeler. That (more or less) is the conclusion of a recent study published in the *Journal of Biogeography* that found extremely small (less than 0.02 mm, or 20 μm, in diameter) microbes could be carried by the wind thousands of kilometers across the sky. Researchers used computer models to send microbes of various sizes into the air from Mexico and the southern tip of South America. They found that very small particles had a high dispersal rate over a 1-year period. They were able to travel between continents, and those smaller than 0.009 mm across reached as far as Australia. On the other hand, the models revealed that microbes larger than 20 μm were not able to travel easily between continents in a single year. As bacteria, amoebae, and some fungal spores are extremely small, the study points out the potential ease with which diseases could be transported through the air over long distances.

Determining Irrigation's Control on Carbon Uptake

A new study that quantifies irrigation's significant impact on agricultural productivity also attests to its influence on the global carbon balance. Published recently in *Global Biogeochemical Cycles*, the research should help to clarify how irrigation is connected to carbon cycles and climate.

The research utilized a model that estimated monthly spatial patterns for 1998–2002 of carbon uptake, nutrient allocation, soil carbon, and carbon dioxide exchange using remotely sensed inputs and climate drivers. The results estimated that the annual global agricultural productivity that results solely from irrigation is equal to about 0.4 petagrams of carbon, which is close to the entire agricultural productivity of the United States.

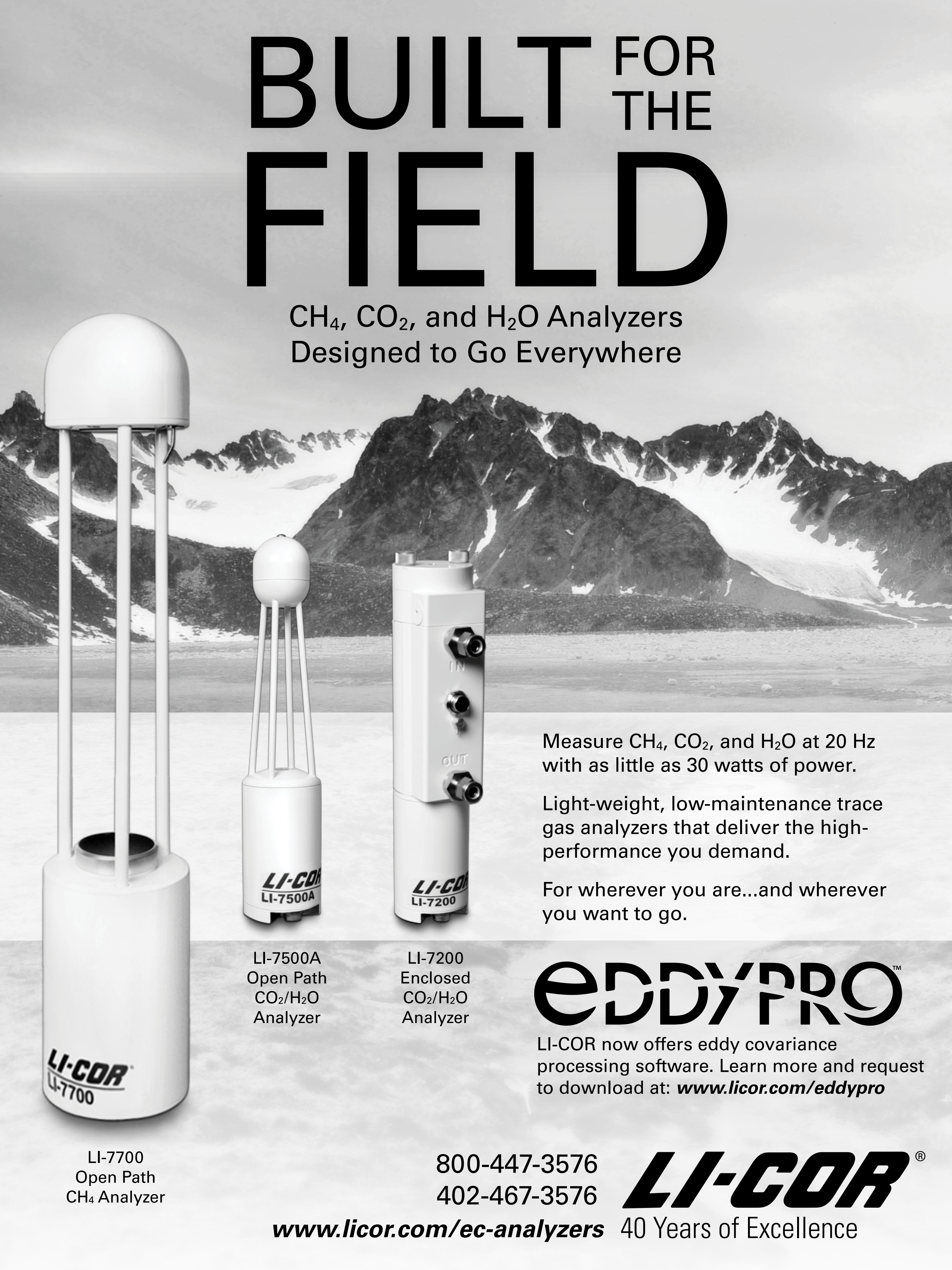
The research also found a nonlinear relationship throughout the world between irrigation's effect on cropland productivity and the level of a region's humidity. That is, a small amount of irrigation water in a drier area has a greater effect on productivity than a large amount in a wetter area.

"More irrigation doesn't necessarily mean more productivity," explains the study's author, Mutlu Ozdogan of the University of Wisconsin—Madison. "There are diminishing returns."

The results of the study suggest the possibility of a global feedback loop that could have a significant climatic impact: a water shortage would lead to less irrigation, a decline in crop productivity, and

ECHOES

> **"All of that is ridiculously dry and boring if you try to describe it in the abstract, but fiction gives us the opportunity to experience the implications of water law viscerally."**
>
> —Paolo Bacigalupi, science fiction author, whose story, "The Tamarisk Hunter," focuses on drought and water laws in the American Southwest. His fiction is part of a collection taking on climate change as the subject and includes stories by TC Boyle, Helen Simpson, David Mitchell, and Margaret Atwood. The collection, published in October by Verso press, was in response to the lack of creative fiction addressing the issue, which author Ian McEwan mentioned last year in *The Guardian*. Look for a full review of the collection in an upcoming issue of *BAMS*. (Source: *The Guardian*)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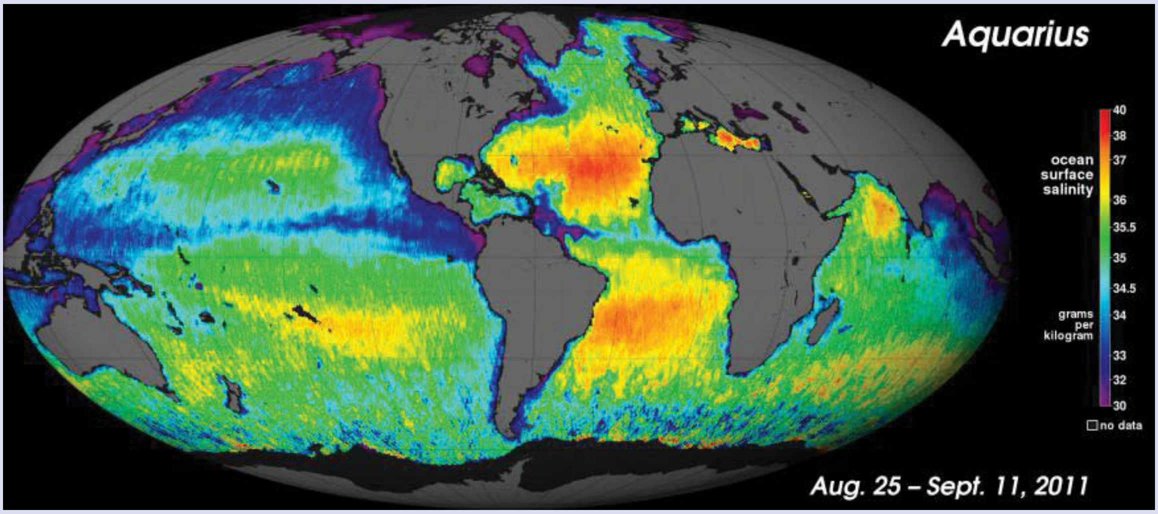
New Map of Ocean Salinity

A collaboration between NASA and Argentina's space agency has yielded a map of the salinity of oceans around the world, which could provide important data in the research of the water cycle, ocean circulation, and large-scale rainfall and evaporation patterns. As discussed in the Nowcast section of the September *BAMS*, the Aquarius instrument on the Argentine SAC-D satellite became operational in late summer and soon after produced data that was utilized to help create the map seen here. The numerical values in the scale represent salt concentration in parts per thousand (grams of salt per kilogram of sea water); the average salinity on the map is about 35. Areas with higher levels of salinity are represented in yellow, orange, and red, while blues and purples depict areas of lower salinity. Black areas indicate gaps in the data. Initial evaluation of the map revealed some notable regional salinity details, such as a greater-than-expected amount of low-salinity water in the area of the Amazon River's outflow. Aquarius, which includes three salinity-sensitive radiometers and a scatterometer that accounts for the roughness of the ocean's surface, and SAC-D will continue until at least mid-2014 to monitor Earth's salinity features in order to help understand their connection to climate and weather.



NASA/GSFC/JPL-CALTECH

less carbon uptake. This could lead to warmer temperatures and less precipitation, which would continue the cycle.

The research should also help in agricultural management.

"Now that we have spatially-explicit maps of how much irrigation is increasing carbon accumulation, we have good information about the value of the water going into those areas," says Ozdogan. "We might be able to come up with a value of carbon [uptake] in those areas as well." (Source: University of Wisconsin—Madison)

Aerosol Experiment Provides Insight into Cloud Formation

The formation of atmospheric aerosols is a key component in understanding how clouds and the climate work. Until now, trace vapors were thought to account for aerosol formation in the lower atmosphere, but a new study shows that they can explain only a small portion of atmospheric aerosol production.

Involving an interdisciplinary team of scientists from 18 institutes in nine countries, the CLOUD (Cosmics Leaving Outdoor Droplets) experiment at CERN (the European Organization for Nuclear Research) is examining the possible link between cosmic rays and cloud formation. Using the Super Proton Synchrotron (SPS) at CERN, this is the first time a high-energy physics accelerator has been involved with a study of atmospheric and climate science. The study's scientists say the results could greatly modify our understanding of clouds and climate.

"These new results from CLOUD are important because we've made a number of first observations of some very important atmospheric processes," explains the experiment's spokesperson, Jasper Kirkby. "We've found that cosmic rays significantly enhance the formation of aerosol particles in the mid troposphere and above. These aerosols can eventually grow into the seeds for clouds."

In the state-of-the-art chamber, atmospheric conditions can be simulated with high control and precision, including the concentrations of trace vapors that drive aerosol formation. The SPS provides an artificial and adjustable source of cosmic radiation.

The scientists discovered that sulfuric acid and water vapor can rapidly form clusters of molecules a few kilometers up in the atmosphere, with cosmic rays enhancing the formation rate more than tenfold. However, in the lowest layer of the atmosphere, within about a kilometer of Earth's surface, additional vapors such as ammonia are needed for formation. The key discovery, however, was that sulfuric acid, water, and ammonia alone—even with the enhancement of cosmic rays—are not sufficient to explain atmospheric observations of aerosol formation. Since this means additional vapors must be contributing, finding out their identity is the next step for the CLOUD researchers.

"It was a big surprise to find that aerosol formation in the lower atmosphere isn't due to sulfuric acid, water, and ammonia alone," says Kirkby. "Now it's vitally important to discover which additional vapors are involved, whether they are largely natural or of human origin, and how they influence clouds. This will be our next job."

The results of the experiment appear in the journal *Nature*. (Source: CERN)

Solar Power Tapped to Cope with Kenya's Drought

Kenya's current drought began last year before the country was able to recover from a severe dry spell in 2008–09. The region's recent droughts have affected farming dramatically and increased the demand for solar-powered weather stations among rural farming communities. The technology holds the promise of alerting farmers to oncoming drought.

FLOATING ABOVE CLIMATE CHANGE

There are many different ideas floating around when it comes to how to prepare for new landscapes attributed to climate change. The biggest one yet involves a country that can float. Anote Tong, the president of the Pacific island nation of Kiribati, is so concerned about climate change affecting the low-lying archipelago that he's considering turning it into a floating island. Likened to a giant offshore oil platform, the project would run a cost of about $2 billion. While he admits it sounds like "something from science fiction" he believes something big needs to be done to save Kiribati from rising sea levels. A smaller idea along the same lines involves floating houses. FLOATEC, a European R&D project, has been working on the design for "amphibian houses" with the Dutch company Dura Vermeer. Over the last 12 years, the company has essentially created a new market in floating buildings. Some of the buildings already completed are the Rotterdam floating exhibition pavilion, a greenhouse built on water, and an amphibious village in Maasbommel, all located in The Netherlands. With the technology in place, the next step rests on governments and local authorities in charge of urban planning. According to Jenny Grote Stoutenburg, a researcher in law from the German Max Planck Institute, "if a threatened island managed to keep an artificial, floating structure, occupied by caretakers, it could probably maintain its claim to statehood." Island or houses, the concept sounds like one that may just stay afloat. (Sources: Yahoo and Eureka)

Kilimo Salama, or safe farming, is a crop insurance program that uses remote solar-powered weather stations to determine compensation for losses from either too much or too little rain. According to the Centre for Training and Integrated Research in Arid and Semi Arid Lands Development (CETRAD), based in Nanyuki in central Kenya, the insurance program has successfully used solar technology to monitor weather patterns in rural farming areas. Local automatic weather stations record data and a corresponding payout is given in the form of seeds to farmers who have experienced crop failure.

CETRAD technician Joseph Ndung'u explains that each automatic weather station is fitted with a general packet radio service (GPRS) device that records data on farms within a 20-km radius every 15 minutes. "Once it has been verified that a farmer has incurred a loss, the crop insurance scheme is then used to determine the level of compensation a farmer is due through seed payoffs," says Ndung'u. "The gadget also has sensors which can measure radiation and temperature, as well as the speed of wind and its direction."

The Kenya Meteorological Department (KMD) is also looking to solar power with the hope it can aid weather forecasting through the use of remote early warning systems. Trials of an early warning system installed at the Dertu Millennium Village project in the northeastern district of Garissa have shown that the technology can help prepare for a potential drought.

According to Samuel Mbalu, database manager at the Millennium Village, the unit installed there collects data on humidity, solar radiation, and winds. Pastoralist Mohamed Abdi Adow says that the information from the station gave him critical information on selling his livestock before the current drought peaked. Mbalu notes that about 300 households are currently benefiting from the technology.

"When we analyze the data and find out that the seasons when we are expecting rain have recorded very small quantities of humidity . . . this is a warning that in the coming months there will be drought," says Mbalu. "So we approach the community to inform them to be prepared to sell some of their cattle, get enough food stocks, and store hay for the remaining livestock."

While scientists debate whether climate change will bring more or less rain to East Africa in the future, solar power will continue to be useful technology for the country. (Source: Reuters)

ECHOES

"That's an insane amount of rain."

—NASA's Stephen Lang, on the 65.06 inches of rain that fell in 72 hours in one area of Japan during Typhoon Talas. The early-September storm was large (420 miles wide) and slow (moving at 11 mph), ideal conditions for drenching rainfall that poured down at 2.6 inches per hour in one location. The storm killed at least 50 people and left 56 more missing. The total amount of rain that fell in Nara Prefecture was 71.08 inches, setting a national record. (Source: LiveScience.com)

Improving Coupling Technologies for Earth System Modeling

As climate scientists wrestle to numerically resolve the numerous atmospheric, oceanic, and land-based components of Earth's climate system, coupling technology has quickly developed to assist with combining the component models for a complete world climate picture. The rapid advance of this technology resulted in a recent workshop to discuss state-of-the-art techniques currently in use for coupling earth system modeling components and to visualize the kinds of innovations that will be required to achieve efficient coupling in next-generation models.

CERFACS (Centre Européen de Recherche et de Formation en Calcul Scientifique) and the Georgia Institute of Technology held the workshop "Coupling Technologies for Earth System Modeling: Today and Tomorrow," in December 2010. Forty-five participants from around the world explored the trade-offs involved in the different approaches to coupling in use throughout the climate modeling community and laid out a vision for coupling Earth system models (ESMs) by the year 2020.

Current coupling technologies can roughly be split into two main categories. The "multiple executable" approach, in which component models remain independent executables, is less flexible and can be less efficient but is straightforward to implement, requiring minimal modification to individual models. The "integrated" monoexecutable approach requires the original codes to be split into initialization, running, and finalization units, and requires some standardization of the resulting component interfaces; however, because components can be run sequentially or concurrently, this approach offers additional optimization opportunities.

For maximum coupling flexibility and efficiency, climate component models should be refactored into initialization, run, and finalization units. However, this refactoring may not be straightforward to apply for some legacy models and it may be difficult to achieve an agreement on the standard component interfaces required for integrated coupling. To satisfy all cases, an

"ideal" coupling technology should therefore offer both approaches. Current research in Generative Programming explores ways to build such an "ideal" technology.

Existing coupling technologies have been developed with different priorities and constraints. In the short term, parallel development of a small number of coupling technologies should continue, each one with a significant amount of resources. However coupler developers should interact more closely and share basic utilities (e.g., regridding libraries) when possible. The development teams should include computing scientists interacting closely with climate modeling scientists. Best practices in coupling should also be discussed, identified, and promoted.

As we move beyond the existing petascale computing and into the exascale era, increased parallelism with more concurrent components seems essential. Moreover, it will be crucial to limit the load of the associated data communication (e.g., by carefully distributing the coupled components over available processes, overlaying communication and calculation, performing redundant calculations, etc.). Future hardware platforms will likely require significant changes in programming structures. If sweeping changes to ESM software are required, the geoscience modeling community should seriously consider combining as much as possible available development resources and evaluate where infrastructure convergence is possible.

For details on the workshop, including the proceedings, abstracts, and links to presentations and commentary, visit the conference website at https://verc.enes.org/models/software-tools/oasis/general-information/events.

—Sophie Valcke (CERFACS) and Rocky Dunlap (Georgia Tech College of Computing)

TECHNOLOGY

Tiny Plane to Take on Hurricane's Strongest Winds

A new miniature plane that may be able to gather data from the eyewall of a hurricane was recently developed in a partnership between NOAA and Embry-Riddle Aeronautical University in Florida. Known as GALE, the 3-foot-long, 8-pound, electric-powered aircraft will be launched like a dropsonde from a hurricane hunter plane into a hurricane's eye, where it will unfold wings and begin recording wind speeds and other atmospheric conditions as pilots on the ground control it by satellite link. As its battery life approaches its 90-minute limit, GALE will be rerouted into the eyewall, where it will no longer be controllable. Although the tumultuous winds of the eyewall will almost certainly destroy the aircraft, researchers hope that before that happens, GALE will collect information that current observational tools cannot measure.

GALE can fly as low as about 100 feet from the ocean's surface—much lower than current hurricane hunter planes—and unlike dropsondes, which take only snapshots of what goes on inside a hurricane, GALE can collect data and stream it to researchers and forecasters in real time.

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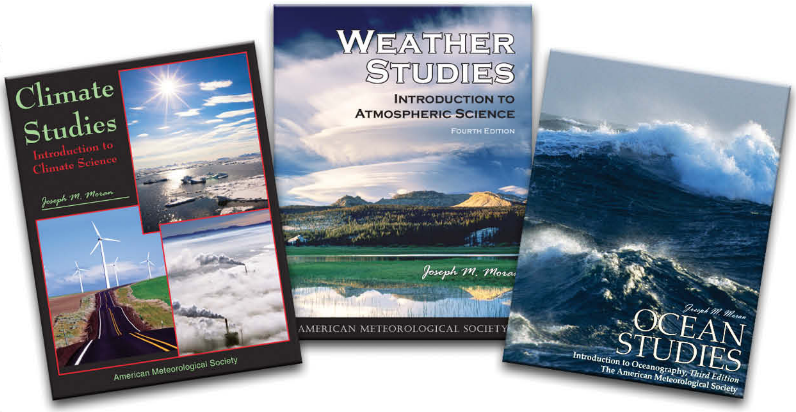

Banner image courtesy of NWS Greenville-Spartanburg

"This device has the potential to gather data we can't typically get," says James Franklin of the National Hurricane Center. "If the aircraft can successfully linger in the hurricane eyewall at very low levels, that would be an exciting advance."

The $30,000 aircraft is scheduled to be flown into hurricanes in 2012. (Source: *South Florida Sun-Sentinel*)

PRODUCTS

Advanced INS/GNSS Inertial Surveying Systems

German manufacturer iMAR GmbH has launched its latest generation of ultra-high precision inertial navigation systems for commercial use. The newest system is the iNAV-FJI-001-J, which is designed for the angular and position reference of laser scanners (LIDAR) and geodetic cameras as well as to aid pilot guidance.

The iNAV-FJI is an inertial navigation system (INS) family of products for inertial navigation, gyro compassing, and dynamical motion measurement with fiber optic gyros that covers applications requiring the highest angular resolution and reliability as well as an open interface to the user.

Key features of this particular INS are the high angular resolution of 0.01 arcsec (< 0.1 μrad) and performance, very high data rate (1,000 Hz), precise time referencing/synchronization, internal data storage, and open interfaces like UDP, TCP/IP, RS422, CAN. The system supports GPS, GLONASS, and is prepared for GALILEO. The system is fully qualified to MIL-STD-810F and MIL-STD-416E.

The system is used for LIDAR and SONAR as well as for georeferencing tasks and can be exported to all European countries, Canada, the United States, Japan, New Zealand, and Switzerland with a simplified export procedure. The system is not covered by any ITAR related export restrictions. On request the same system is also available with ring laser gyro (RLG) technology (iNAV-RQH-10018).

For more information visit www.imar-navigation.de.

ECHOES

"Maybe this isn't just a wave problem . . . let's step out of the box and say maybe there's atmospheric variation going on."

—Tim Janssen, associate professor of oceanography at San Francisco State University, on new research that suggests atmospheric pressure may play a role in rogue waves. When oceanographers from Japan and Norway analyzed wind and wave records in the North Sea from 2003 to 2005, they found that the conventional analysis known as the Benjamin-Feir instability index, thought to show areas where huge waves are more likely based on the conditions of the ocean, did not correlate to the days with records of two or more rogue waves. Janssen explained that the peak wind speed for the day, rather than average wind speed, might be a better indicator of rogue wave conditions, which is not surprising since changes in pressure influence changes in wind speeds. Although the relationship between giant waves and atmospheric conditions was identified, the nature of that relationship is not yet known and the researchers plan to explore the subject further. (Source: OurAmazingPlanet.com)

IN BOX
INSIGHTS and INNOVATIONS

Climate Change and Carbon Threats to Coral Reefs

National Meteorological and Ocean Services as Sentinels

BY CLAIRE M. SPILLMAN, SCOTT F. HERON, MARK R. JURY, AND KENNETH R. N. ANTHONY

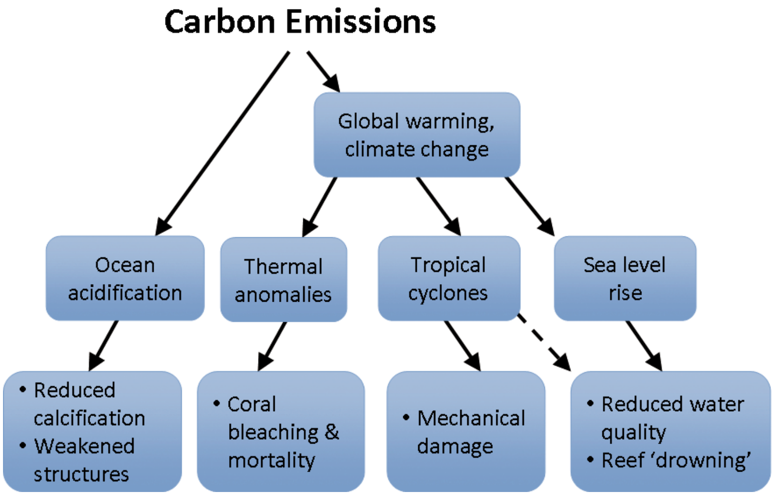

Fig. 1. Links between carbon emissions and factors reducing coral reef resilience due to ocean acidification, warming, tropical cyclones, and sea level [adapted from Anthony and Marshall (2009)].

The preservation of coral reefs under a changing climate requires a coordinated approach that integrates observational, experimental, and modeling efforts with practical management and sound government policy. Coral reefs are among the most species-rich habitats in the world, but also among the most vulnerable to our current high-emission path. Observations of the climate system have shown an increase in global average surface temperature during the twentieth century, with an increased rate of warming since 1950. This has been attributed to increased levels of anthropogenic carbon dioxide (CO_2) in the atmosphere since the preindustrial era, primarily due to the human activities of fossil fuel combustion and forest logging. The Intergovernmental Panel on Climate Change (IPCC)'s 2007 *Fourth Assessment Report* states that warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.

Ocean warming increases the risk of extensive coral bleaching events and mass mortalities. Ocean acidification, via increased absorption of CO_2 by seawater, can reduce the capacity of coral reefs to grow and maintain their structure and function. Many of the world's coral reefs are already degraded due to marine pollution, overfishing, and local-scale disturbances; to ensure reefs can cope with potential impacts of global warming and ocean acidification, improved reef management is essential.

Here, we summarize some of the linkages between atmospheric CO_2 and the physical and chemical processes that it drives: climate change, increased sea surface temperatures, ocean acidification, tropical cyclone frequency/severity, and sea level rise (Fig. 1). We then draw links between these processes and specific threats to coral reef ecosystems. Finally, we propose a strategic framework for how observations and forecasting systems can be coordinated as part of national meteorological and ocean services, alerting reef managers

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DOI:10.1175/BAMS-D-11-00009.1

and policy makers to areas at high risk from both local and global pressures.

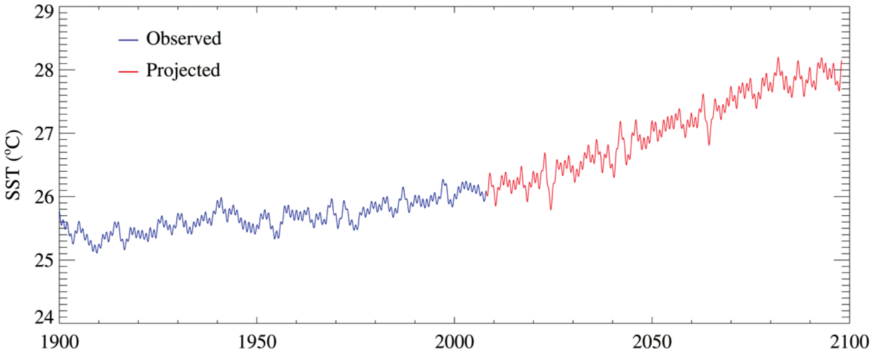

Fig. 2. Time series of NOAA observed and GFDL model-projected SST in the zone 30°N–30°S based on IPCC-AR4 A1B scenario, both smoothed with an 18-month running mean. Data derived from the International Research Institute for Climate and Society (IRI) database (http://iridl.ldeo.columbia.edu).

CLIMATE CHANGE AND CORAL REEFS.

Warming of the tropical oceans is one observed manifestation of changes in the climate system (Fig. 2). Elevated ocean temperature has been established as the primary cause of mass coral bleaching events. Coral bleaching results from the loss of symbiotic algae from coral tissues during times of stress. Mortality, due to bleaching and/or subsequent disease, can occur following prolonged thermal stress, leading to loss of reef structure and habitats. The intensity and scale of observed bleaching events have increased since the 1960s, and major bleaching events in 1997–98 (Fig. 3), 2002, 2005, and 2010 have impacted entire reef systems. Projections for most IPCC scenarios predict a rise in sea surface temperatures (SST) of at least 2°C in the twenty-first century (Fig. 2). This is likely to push most coral reefs close to or beyond their threshold for bleaching more often, reducing their ability to recover from such events.

Coral reefs are also under growing threat from ocean acidification, resulting from increasing CO_2 concentrations in the atmosphere. Increased absorption of this CO_2 by ocean surface waters leads to a decline in marine pH and a reduction in the concentration of carbonate ions, the building blocks for corals. The consequences will be several-fold. First, acidification leads to reduced coral growth, potentially promoting a shift from net reef growth to net dissolution. Second, reduced calcification will lead to a weakening of reef structures, and hence increased vulnerability to storm damage. The combined effect for coral reefs is reduced resilience and ecosystem function. With CO_2 concentrations predicted to rise further in the twenty-first century, the rapid change in ocean carbon chemistry is likely to outpace the potential for evolutionary adaptation to ocean acidification.

A warming climate is also likely to affect the frequency and intensity of tropical cyclones (hurricanes, typhoons), as warm sea surface temperatures are necessary for cyclogenesis. Some studies suggest an increase in the severity of storms but a decrease in the number of events under climate change, though this is still under debate within the scientific community. Cyclones can be extremely destructive to coral reefs, as the waves they generate can relocate large coral colonies and reduce reefs to rubble (Fig. 4). Reefs already weakened by bleaching and ocean acidification will be at greater risk of physical destruction from tropical cyclones. However, storms can also mitigate thermal bleaching risk, as localized cooling can result from wind-driven water mixing and increased

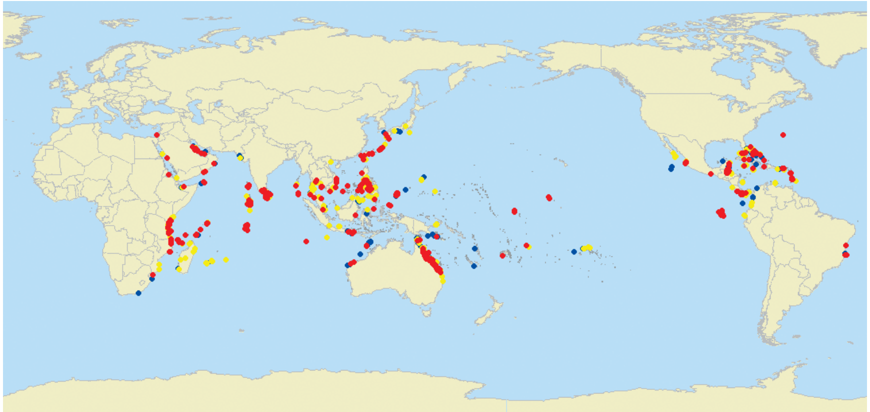

Fig. 3. Location of the coral reefs affected in the 1997–98 global bleaching event. Red, yellow, and blue dots indicate severe, moderate, and low bleaching, respectively (Reefbase; www.reefbase.org).

cloud cover, while the latter also reduces light pressure to ameliorate bleaching risk.

Sea level rise is another consequence of climate change. Since 1990, global warming has contributed approximately 1.6 mm per year to global average sea level (Fig. 5), which is estimated to increase by as much as 60 cm during this century. Sea level rise over coral reefs provides corals with greater space to grow upward. It is possible for coral reef growth to keep pace with gradual sea level rise unless compromised by ocean acidification. However, increasing water depth and reduced water quality from enhanced sediment suspension can reduce light availability and may cause deeper coral reefs to "drown" if they do not receive enough sunlight to support photosynthesis.

The downstream consequences of CO_2 emissions, via ocean acidification and ocean warming driven by climate change, intense storms, and sea level rise (Fig. 1), can have far-reaching implications for the health and functioning of coral reef ecosystems. Importantly, global impacts of increased CO_2 are likely to occur in combination with regional or local-scale disturbances already experienced by many coral reefs, such as poor water quality and destructive fishing practices. These can act together to significantly degrade the resilience of coral reefs to the point that reefs are unable to recover from even minor disturbances. Coordinated action at national levels to promote management for reef resilience is imperative to secure the survival of global coral reefs under climate change and ocean acidification.

Fig. 4. A Porites colony in Western Australia was propelled onto the reef flat as Cyclone Fay passed in Mar 2005 (Australian Institute of Marine Science).

THE ROLE OF METEOROLOGICAL AND OCEAN SERVICES. With growing recognition of the potential impacts of global change on coral reefs and coastal ecosystems, meteorological and ocean services are increasingly called upon to provide support to real-time oceanography, marine biology, and coastal management. Here, we suggest a framework for the role of meteorological and ocean services in providing information and forecasts for coral reefs that consider multiple environmental factors at different temporal and spatial scales (Fig. 6).

Participation in (and support of) regional and global observation networks is an important role of meteorological and ocean services. Meteorological services participate by contributing observations, providing instruments and processing, and transmitting and storing data. In turn, they benefit from access to extensive datasets that can be used to develop and implement a broad range of ocean products and services, including those needed to monitor and protect coral reefs (Fig. 6). Examples of such products include those developed by the NOAA Coral Reef Watch program for determining coral bleaching and disease risk due to thermal stress using satellite-derived SST. Additionally, NOAA also provides in situ oceanographic monitoring at tropical reef locations. In addition to observation-based nowcasts and reanalyses, high-quality data are essential for accurate numerical weather prediction (storms and waves), seasonal forecasting (thermal stress), and climate modeling (ocean acidification and sea level rise).

Numerical weather prediction has long been an undertaking of national meteorological services, with forecasts of events such as cyclones and storm surges produced operationally. In recent decades, these capabilities have expanded to include ocean forecasting, both on seasonal and climatic timescales, as recognition of the impact on regional climate of large-scale drivers such as the El Niño–Southern Oscillation has increased. The Australian Bureau of Meteorology currently provides global seasonal ocean forecasts,

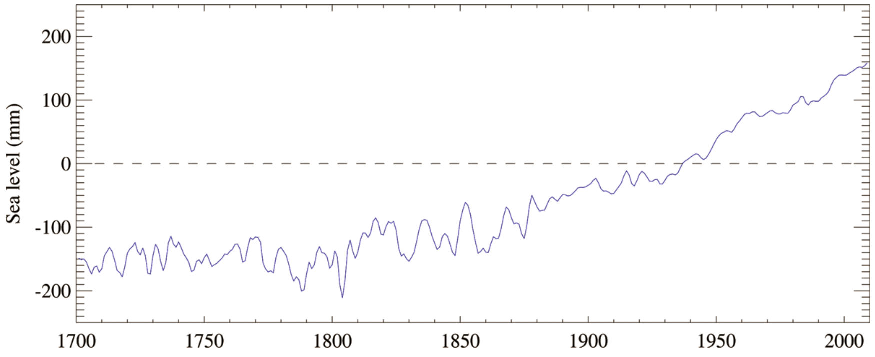

Fig. 5. Time series of sea levels averaged over the zone 30°N–30°S, based on gauge data from the Joint Archive for Sea Level (JASL; http://ilikai.soest.hawaii.edu/UHSLC/jasl.html), accessed via Climate Explorer (http://climexp.knmi.nl).

high-resolution five-day ocean forecasts (BLUElink), tidal predictions, tsunami warning services, and ocean surface wave predictions. In particular, seasonal dynamical SST forecasts are provided using the Predictive Ocean Atmosphere Model for Australia (POAMA) for the monitoring of coral bleaching risk on the Great Barrier Reef. NOAA also produces a global statistical seasonal outlook for thermal stress for reefs. Such advance warning of anomalous warm conditions and other threats to reef health allows for proactive management.

Observations, data-based products, and model forecasts provided by national meteorological and ocean services—both currently and in the future—could be used to inform reef warning systems. However, often these products are not integrated to form a coordinated, tailored service for reef management. National meteorological services are the logical agencies to coordinate such systems, due to their strengths in numerical prediction, climate modeling, and operational capabilities. The development of multifaceted systems that include information and forecasts of tropical cyclones, storm surge, and thermal stress on daily-to-seasonal time scales, together with predictions for ocean acidification and sea level rise at decadal time scales, is crucial for best-practice reef management. The inclusion of both pulse-type risks (stochastic disturbances) and press-type stressors in an alert framework allows for better future planning, public education, and proactive management responses to reef threats, and also provides improved guidance for government policy and increased global awareness of the impacts of climate change on coral reefs.

Targeted reef services must be well designed in order to reliably provide useful information in near real-time that allows for rapid management responses to reef threats. National meteorological services often have the mandate and operational infrastructure to support products that research institutes lack, emphasizing their role as the logical coordinator of such systems. Formal communication pathways between relevant agencies are essential to insure systems meet the requirements for effective reef management. The use of interactive viewing platforms that allow the simultaneous display of multiple products, plus well designed websites that draw together all available resources in a clear and logical manner, are excellent tools in creating a usable reef service. As public engagement is important for promoting stewardship of coral reefs, tools that can also be utilized for community

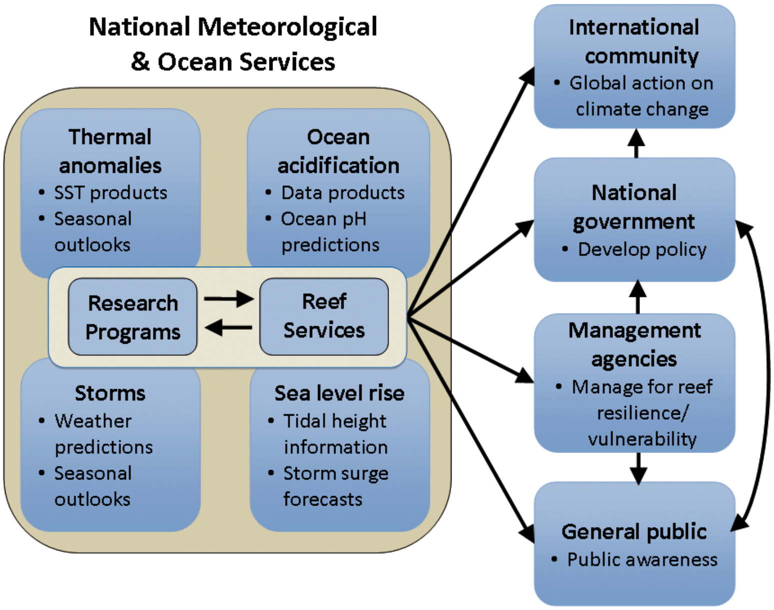

Fig. 6. Framework describing the role of national meteorological and ocean services in addressing carbon, climate change, and coral reef issues.

education are doubly useful. Lastly, integration of reef ecosystems research into the development of systems that alert management agencies to coral reef threats is an important feedback mechanism for continuous improvement of forecasting capabilities.

THE WAY FORWARD. The development of operational cross-disciplinary reef services will provide improved risk and vulnerability assessments for coral reefs, and can assist in the development of monitoring, conservation, and adaptation strategies. First, for the development of effective systems, close collaboration between meteorological and ocean services, reef management agencies, and the science community is essential. Systems must address the requirements of reef management agencies and be useful, reliable, and informative, with limitations well documented. Collaborative programs between management agencies and meteorological services can develop plans for warning systems and determine how they would best be assimilated into existing response plans and management frameworks.

Second, the creation of multidisciplinary, cross-institutional research programs that underpin such services is important, particularly for the investigation of reef ecosystem responses to global warming and ocean acidification, and assessment of associated impacts on ecological, social, and economic systems. Further research is required to enhance modeling capabilities, particularly in determining the impacts of climate change on large-scale drivers and subsequent teleconnections with reef regions, coastal circulation, cyclone generation, and wave regimes. This would lead to improved predictions, assessments, and management of the impacts of climate change and ocean acidification on coral reef systems.

Targeted, coordinated reef services, which incorporate the multiple threats of storm surge, thermal stress, ocean acidification, and sea level rise, are recommended to help address the substantial challenge of securing the long-term health and resilience of coral reefs. Other coastal ecosystems and communities that are similarly at risk under climate change will also benefit from such integrated systems. Provision of reliable forecasts, high-quality data, and applied reef products at multiple scales will enable reef managers and stakeholders to plan better for local-scale disturbances as well as climate change. The interactions and potential feedbacks between global CO_2 effects and local/regional disturbances affecting reef health heighten the urgency of the development of coordinated strategies for reef conservation.

ACKNOWLEDGMENTS. The authors would like to thank M. V. K. Sivakumar (WMO) and Peter Dexter (Bureau of Meteorology) for initializing this discussion and for their helpful suggestions. The manuscript contents are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the U.S. Government, nor on behalf of the Australian Institute of Marine Science or the Australian Government.

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Web Resources

Operational BLUElink and POAMA forecasts:
http://www.bom.gov.au/oceanography

NOAA Coral Reef Watch:
http://coralreefwatch.noaa.gov

Advances in Forecasting Coral Bleaching Conditions for Reef Management

BY CLAIRE M. SPILLMAN

Anomalously warm ocean temperatures are the primary cause of mass coral bleaching events. Bleaching is a stress response of corals, the unfavorable conditions causing corals to expel their zooxanthellae, giving rise to the typical white coloration observed (Fig. 1). Major bleaching events tend to occur during the warmest months, with coral mortality determined by how much and for how long temperatures remain above the maximum mean summer temperatures. Basin-scale climatic processes such as the El Niño–Southern Oscillation (ENSO) can influence bleaching risk, with most mass bleaching events occurring during strong El Niño periods, due to sustained regional elevations of ocean temperatures. Aside from thermal stress, other stressors such as tropical cyclones, freshwater

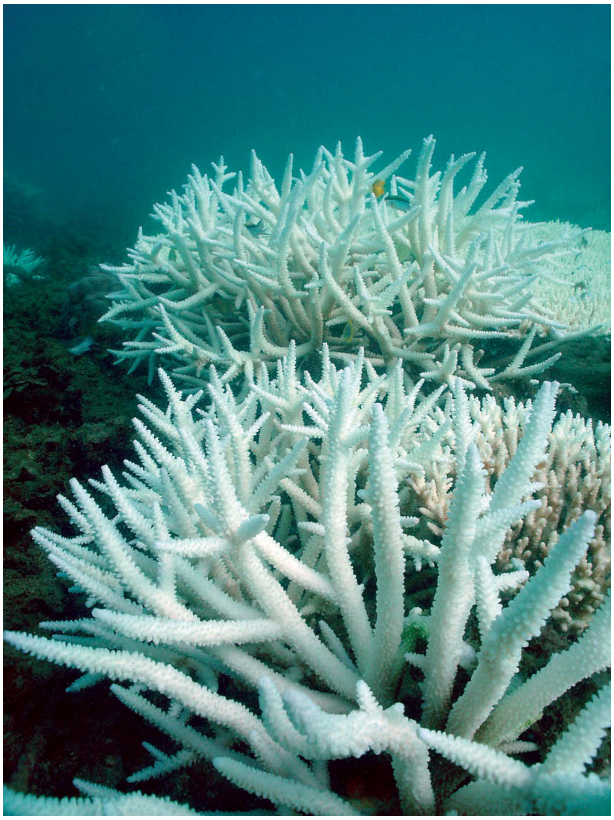

IMAGE: COMMONWEALTH OF AUSTRALIA (GREAT BARRIER REEF MARINE PARK AUTHORITY)

FIG. 1. Bleached staghorn corals on Keppel Island Reefs, Australia.

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DOI:10.1175/BAMS-D-11-00065.1

inflows, and anthropogenic pollution can also induce bleaching, but to a far lesser extent and generally not on large spatial scales.

Coral bleaching is expected to increase in both severity and frequency under global warming. This predicted increased occurrence of mass bleaching events reinforces the urgency of gaining insight into the processes of coral bleaching, in addition to the development of effective management plans to minimize reef damage during such events. Coral reefs are renowned for their biological diversity and high productivity, and annually generate billions of dollars of income from and resources for tourism, fishing, building materials, and coastal protection. The ability to forecast potential bleaching conditions and mass events in a particular region using both climate models and statistical schemes is a new and valuable tool in the management and conservation of such sensitive systems. Climate models can be used in a variety of ways to predict reef vulnerability, from seasonal bleaching risk to long-term impacts under climate change.

Here we describe advances in seasonal forecasting of ocean conditions for use in coral reef management, specifically predictions of coral bleaching risk.

FORECASTING CORAL BLEACHING. Until recently, predictions of coral bleaching risk were predominantly based on satellite-derived nowcasts or climate-scenario projections on decadal timescales. Nowcasts are generally of high spatial resolution, often at reef scales (e.g., NOAA Coral Reefwatch satellite-based products, CSIRO ReefTemp), and can be very useful in highlighting areas currently experiencing bleaching or that have recently been subject to thermal stress. However, although these products provide a snapshot of the current ocean state, they can only offer limited advance warning of anomalously warm conditions as persistence forecasts. Similarly, while climate change projections underscore the sense of urgency for long-term planning for improved reef resilience and the push for action on the issue of global warming, they do not practically assist reef managers in the short term. Predictions on a seasonal time scale are more practical for reef managers, as strategies can be implemented at the start of summer prior to the anticipated onset of bleaching. Advance warning of potential bleaching events allows for proactive planning and response, as well as the timely implementation of management plans to reduce reef damage and maximize the potential for recovery.

Seasonal prediction schemes, using either statistical or dynamical models, can be used to address this current deficit by providing forecasts of bleaching risk for coming months. A primary distinction between these two types of models is that statistical models use historical data and empirical relationships to predict future events, while dynamical models use recent observations and the principles of physics to provide predictions. Statistical models can often be quite skilful, though they assume a constant climate baseline and thus may not capture future climate changes. However, statistically based forecast products such as the NOAA Coral Reef Watch Seasonal Coral Bleaching Thermal Stress Outlook have been relatively successful in forecasting upcoming summer conditions and potential bleaching risk globally, and are utilized by reef managers.

In contrast, global circulation models (GCMs) are dynamical multivariate models, composed of differential equations based on the fundamental laws of physics and fluid motion. GCMs can simulate system responses to a changing climate, though a detailed understanding of the processes involved is required. The Predictive Ocean Atmosphere Model for Australia (POAMA), developed by the Australian Bureau of Meteorology and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), is currently the only dynamical prediction system used for operationally forecasting coral bleaching risk on a seasonal time scale. Operational forecasts of sea surface temperature (SST) anomalies in the Great Barrier Reef (GBR) region (Australia) are generated using POAMA in real time and updated daily online. Probabilistic forecasts are also produced, and provide the user with both the likelihood of bleaching conditions occurring and an estimate of forecast uncertainty, which is useful for risk assessments. These forecasts are an important component of the Great Barrier Reef Marine Park Authority (GBRMPA) Coral Bleaching Response Plan.

POAMA FORECASTS. POAMA is a global seasonal ensemble prediction system, consisting of a coupled ocean–atmosphere model and initialization systems for the ocean, land, and atmosphere. In the real-time system, a nine-month forecast is produced each day starting from the latest observed initial conditions. A 30-member ensemble is created by combining the daily forecasts from the past 30 days, in what is termed a time-lagged ensemble. The variability of the results among forecasts for a given forecast issue date gives an indication of the possible spread or uncertainty in the future evolution of the climate system. An ensemble

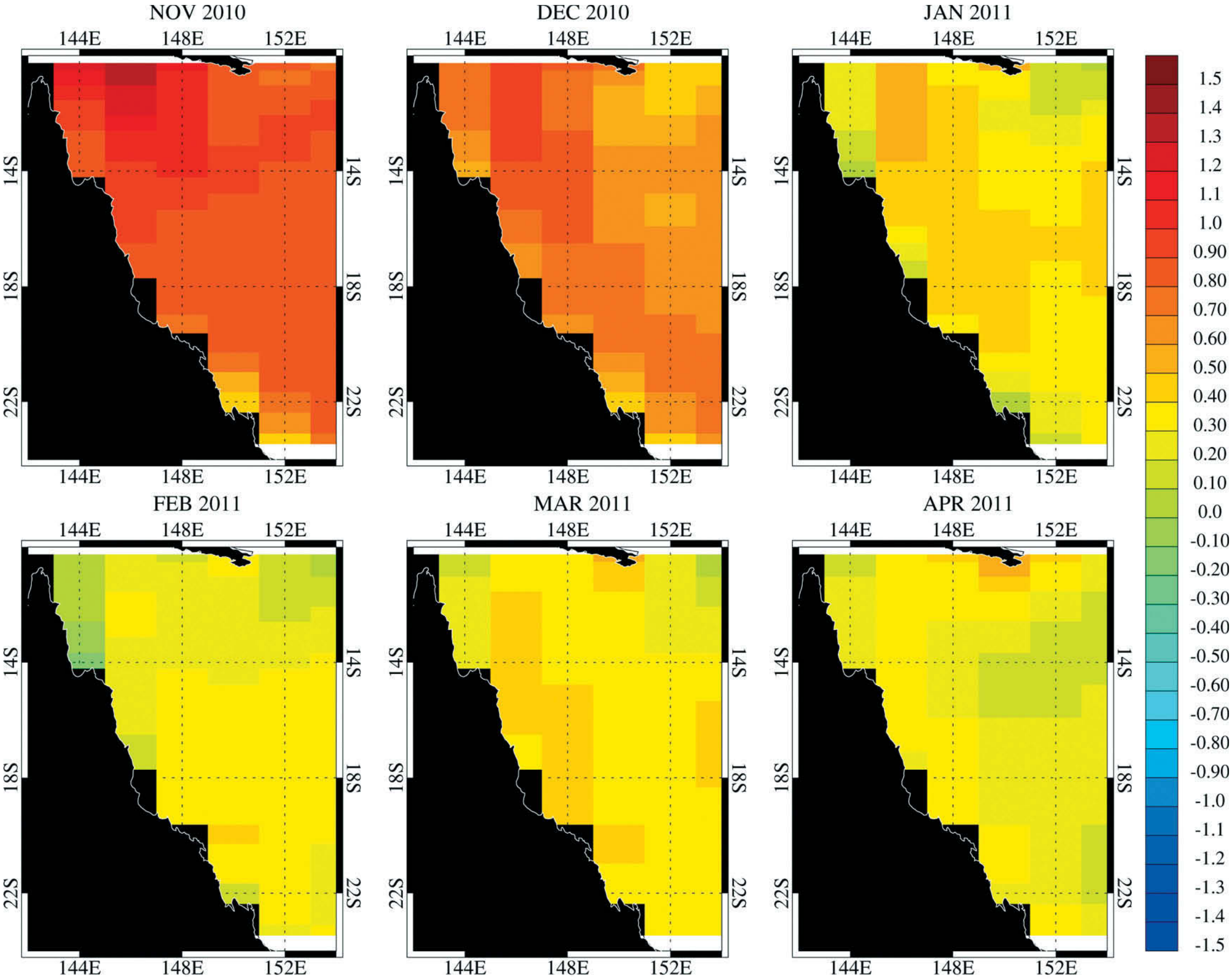

Fig. 2. Operational POAMA forecast of monthly ensemble mean SST anomalies (°C) in the GBR region issued on 1 Nov 2010.

mean is then created by averaging these 30 forecasts. The skill of the system is based on the ability of the model to predict past events, and is calculated using a model hindcast dataset for 1982–2006.

Since 2009, two operational products for the GBR have been produced daily in real time and uploaded for public access. The first is the ensemble mean spatial forecast of SST anomalies across the GBR (e.g., Fig. 2). The second is the GBR Index, defined as the spatial average of SST anomalies over the region (e.g., Fig. 3), where the ensemble mean is presented together with the 30 daily GBR Index forecasts, providing information as to the likelihood of anomalous temperatures as well as the uncertainty in the forecasts. These forecasts have been demonstrated to have useful skill up to three months into the future during the summer months, and they captured both the 1998 and 2002 GBR bleaching events. Experimental forecasts of the probability of SST anomalies exceeding 0.6°C in the GBR, a useful management threshold supplied by GBRMPA, are also produced as a research product.

Experimental monthly SST anomaly and probabilistic forecasts for the tropical oceans (45°S–45°N) are also produced daily. Additionally, a new monthly POAMA thermal-stress forecast product, degree heating months (DHM), is currently under development. Degree heating months are calculated as the sum of positive SST anomalies referenced to the long-term mean temperature of the warmest summer month over a rolling three-month time period, and are based on similar weekly products produced by the NOAA Coral Reef Watch program. These forecasts have been shown to capture observed past patterns of thermal stress, including skillful predictions for the severe 1997–98 global and 2005 Caribbean bleaching events (Fig. 4). Forecasts for the tropical oceans are available online as research products for viewing in Google Earth™ (Fig. 5).

Forecast presentation and delivery are very important, and the innovative use of more interactive platforms such as Google Earth can lead to an improved user understanding of the products (Fig. 5). Large spatial regions can be viewed and zoomed, and images animated, demonstrating the way forecasts change with lead time into the future. Google Earth images of POAMA forecasts also depict the ocean-model horizontal grid spacing (0.5°–1.5° in the meridional direction, 2° in the zonal direction), which assists in developing user appreciation of model capability and resolution limitations. An additional benefit is that products and information from other institutes may be viewed simultaneously and overlaid to provide composite images that can be useful in planning activities. Furthermore, the use of these types of interactive viewers, rather than sometimes esoteric static plots, can result in better engagement of the general public and improved community awareness.

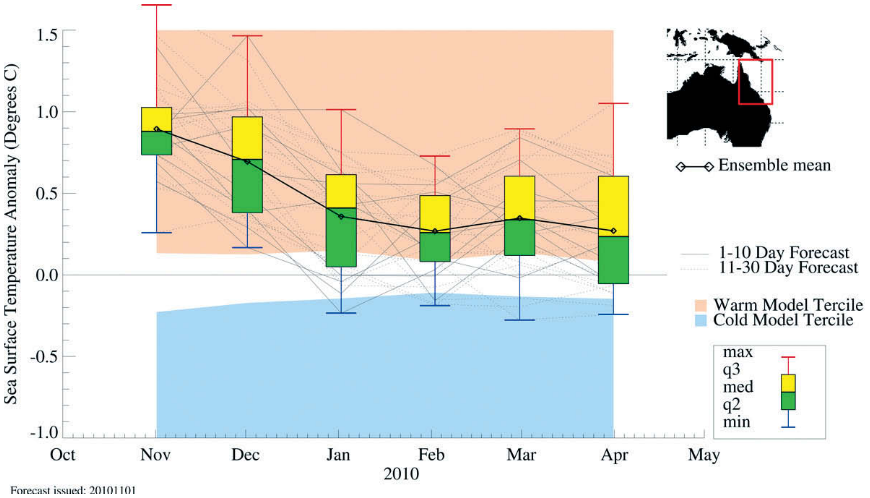

Fig. 3. Operational POAMA forecast of monthly GBR Index values issued on 1 Nov 2010. Overlaid is the ensemble mean (black) and the last 30 forecasts comprising the ensemble (grey). The shading indicates upper and lower climatological terciles from the POAMA hindcasts.

There are several advantages to using seasonal POAMA forecasts for coral reef management. POAMA is a fully coupled dynamical system that assimilates the latest observations, avoiding the pitfalls associated with statistical models built on historical data, when baselines can shift under a changing climate. Forecasts are fully operational, produced in real time and available online so that managers can readily access the most up-to-date information. Probabilistic POAMA forecasts assist reef managers by providing the likelihood of warm conditions occurring and an estimate of forecast confidence. Forecast probabilities can also be utilized for cost/benefit analyses and risk assessments. Finally, the skill of the system has been demonstrated as useful for both the GBR and across the tropical oceans, providing scope for further applications to global reef regions.

USES IN REEF MANAGEMENT. Seasonal forecasts are a valuable tool in reef management, allowing for proactive management responses and the early implementation of preventative measures. POAMA forecasts for the GBR form an important component of the Early Warning System in the GBR Marine Park Authority Coral Bleaching Response Plan. The Coral Bleaching Response Plan is a strategic framework comprising an early warning system and an assessment and monitoring component. The early warning system consists of three stages: climate monitoring, sea-temperature monitoring, and monitoring of bleaching by the general public and tourist operators. POAMA seasonal forecasts for the GBR form an important part of the first stage, providing outlooks of potential bleaching conditions for the upcoming summer.

Mass coral bleaching itself cannot currently be prevented, but policies can be implemented to limit reef damage and aid recovery. Management strategies can include limiting access to affected areas to maximize resilience by reducing other stresses (e.g., setting temporary Marine Protection Areas; artificially shading or cooling selected reefs; and enhancing the overall health of the reef by reducing pollution, coastal runoff, and overfishing). Currently, seasonal forecasts of bleaching risk are most valuable in directing resources and focusing monitoring to increase knowledge of the evolution, causes, and consequences of bleaching. Often, the first knowledge of coral bleaching in a particular area is after the fact, and so the capacity for coordinated monitoring prior to and throughout the bleaching event is invaluable. Briefing government

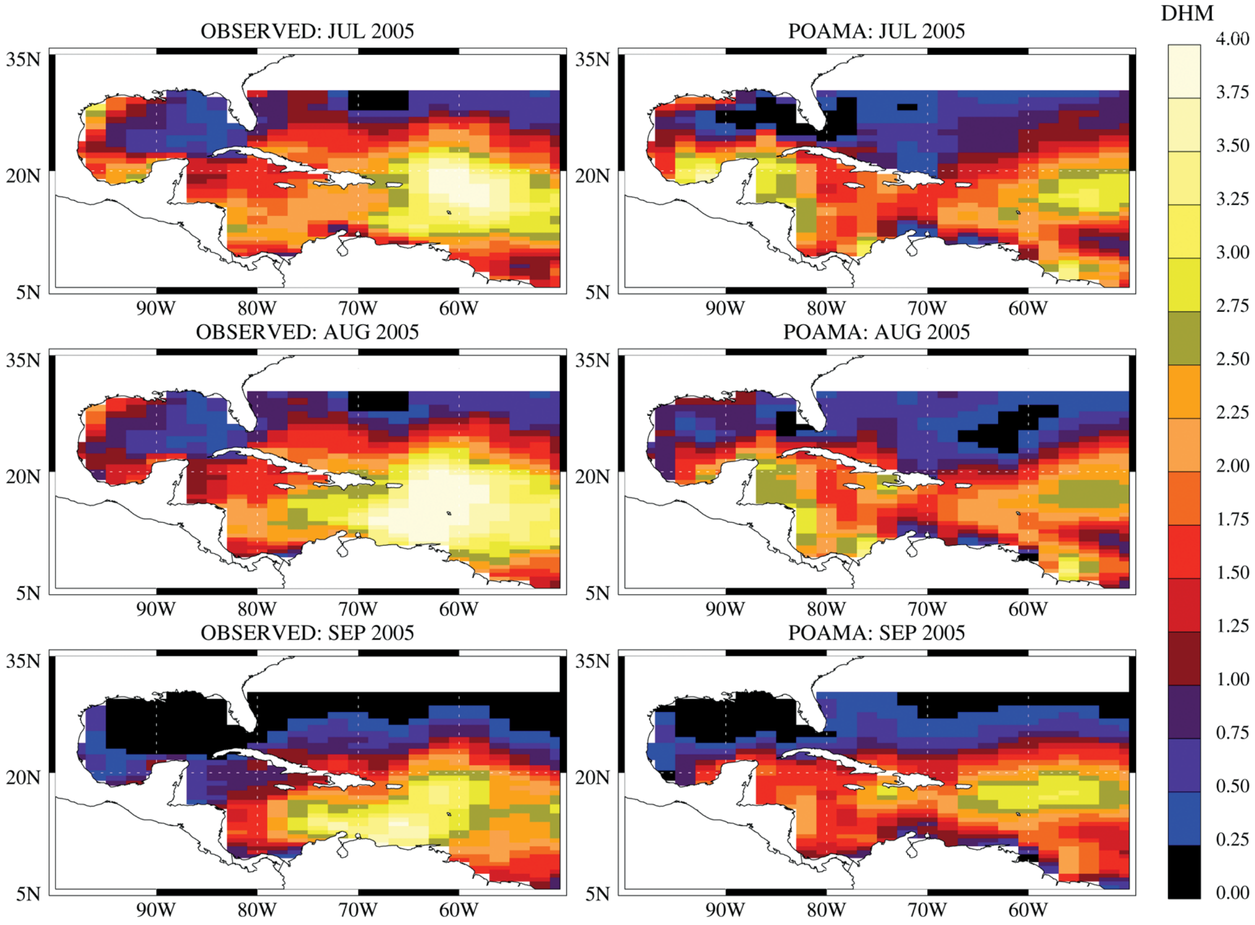

Fig. 4. Observed (Reynolds OIv2 SST products) DHM values and POAMA ensemble mean DHM (°C) hindcasts for Jul–Sep 2005 in the Caribbean region. [Adapted from Spillman et al. (2011)]

departments and funding bodies, in addition to educating the general public and tourism industries, are also important uses of the forecasts.

CONCLUSIONS. Forecasts on a seasonal time scale are particularly useful for reef managers as they provide advance notice of potential bleaching conditions, allowing for proactive management responses to bleaching events. POAMA is the first example of the use of a dynamical GCM in the prediction of coral bleaching conditions, and has become an important component in management plans and strategic frameworks for the Great Barrier Reef. Future versions of POAMA will include an upgraded ocean data assimilation scheme and expanded ensemble prediction system, which are expected to improve ocean forecasts. Seasonal forecast products have revolutionized the way in which coral bleaching events are predicted, monitored, and assessed. Skillful seasonal forecasts of future coral bleaching risk in real time are an invaluable tool for future reef management and conservation under a changing climate.

ACKNOWLEDGMENTS. The author would like to thank the Great Barrier Reef Marine Park Authority—particularly Paul Marshall and Roger Beeden—for their support and enthusiasm. Thanks also to Oscar Alves, Debbie Hudson, Lynda Chambers, and Amanda Amjadali, all of the Australian Bureau of Meteorology, for their review of previous versions of this manuscript.

FOR FURTHER READING

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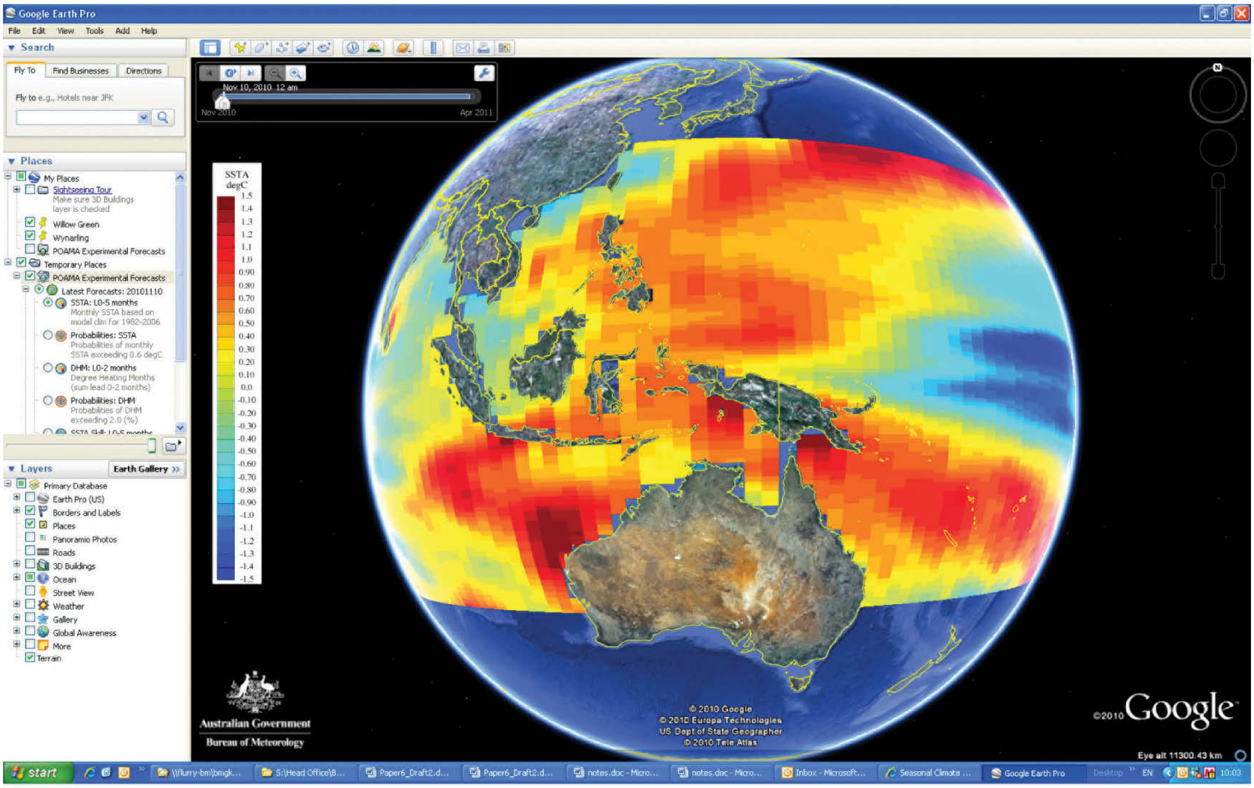

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Fig. 5. Screenshot of POAMA SSTA forecast for the tropical oceans in Google Earth.

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Web Resources

Operational POAMA forecasts:
http://www.bom.gov.au/oceanography/oceantemp/GBR_SST.shtml

Experimental POAMA forecasts:
http://poama.bom.gov.au

NOAA Coral Reef Watch:
http://coralreefwatch.noaa.gov


Sticky as Treacle: Caught in the Boston Molasses Flood of 1919
weatherwise
JANUARY / FEBRUARY 2011
WWW.WEATHERWISE.ORG
Flash and Fire:
Volcanic Lightning
The 2009-2010 Snow Report
The Meteorological Phenomenon That Parted the Red Sea

ACCELERATION OF LAND SURFACE MODEL DEVELOPMENT OVER A DECADE OF GLASS

BY BART VAN DEN HURK, MARTIN BEST, PAUL DIRMEYER, ANDY PITMAN, JAN POLCHER, AND JOE SANTANELLO

The Global Land Atmosphere System Study has ushered in an era in which LSMs for numerical weather prediction and climate prediction now incorporate complex vegetation responses, detailed hydrology, dynamic snowpack evolution, urban processes, and more.

Land surface models (LSMs) used in numerical weather prediction and climate projections have seen considerable development since the early simple "bucket scheme" of Manabe (1969). From the pioneering work by Deardorff (1978), the development of globally applicable LSMs by Dickinson et al. (1986) and Sellers et al. (1986) and the building of the first models that represent vegetation dynamics (e.g., Foley et al. 1996), LSMs now represent heterogeneity, complex vegetation responses to environmental conditions, detailed surface and subsurface hydrology, dynamic evolution of snowpacks, and even representations of urban, lake, and biogeochemical processes. A thorough review of the present state of the art in land surface modeling would probably require tens if not hundreds of pages to address all of the relevant developments [see Levis (2010) for a recent review]. Here we present an overview of initiatives that are a part of the Global Land Atmosphere System Study (GLASS; available online at www.gewex.org/glass),[1] including the antecedent community modeling efforts that led up to the formation of GLASS. Reference will be made to a number of projects in which GLASS is involved. An overview of these can be found in Table 1.

There has long been recognition of the need to confront LSMs with observational data. However, in the early 1990s, Henderson-Sellers et al. (1993) appreciated the need to evaluate and intercompare LSMs within a *common framework*. She launched the Project for the Intercomparison of Land-Surface Parameterization Schemes [PILPS; the first model

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-11-00007.1

In final form 28 April 2011

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[1] GLASS is one of the scientific panels under the umbrella of the Global Water and Energy Cycle Experiment (GEWEX), a core project of the World Climate Research Programme (WCRP).

intercomparison project (MIP)], with the aim of *improving the understanding of current and future parameterization schemes used to represent regional to continental scales.* PILPS was sponsored by the World Meteorological Organization's Working Group on Numerical Experimentation (WGNE) and the GEWEX science panels. The first meeting was held in June 1992 in Columbia, Maryland. PILPS was singularly successful. Through the 1990s–2000s it coordinated multiple offline (uncoupled from atmospheric models) experiments, first with synthetic atmospheric forcing (Pitman et al. 1993) and later with observed forcing. The first of these (Chen et al. 1997; see Fig. 1) used data from the atmospheric boundary layer research station at Cabauw in the Netherlands to produce one of the most highly cited papers in land surface modeling and to establish the weaknesses inherent in the Manabe (1969) scheme, as well as the failure of many LSMs at that time to conserve energy and water. Increasingly well-constrained experiments followed, focused mainly on mid- and high-latitude regions. For example, Wood et al. (1998) and Liang et al. (1998) focused on the Red–Arkansas River basin in the central United States; Schlosser et al. (2000) and Slater et al. (2001) concentrated on the boreal grasslands in Valdai, Russia; and Nijssen et al. (2003) and Bowling et al. (2003) examined the Torne–Kalix basin in Sweden.

PILPS's significant and ongoing contribution has been to facilitate the testing and intercomparison of LSMs against point-based observational data. Many of the technical challenges that PILPS helped resolve are now commonly implemented in LSMs—issues such as the need to run LSMs decoupled from the host atmospheric model, and the recognition of the need to formally conserve energy and water. PILPS was also originally conceived to compare LSMs in the coupled environment. While efforts to examine the coupled behavior of LSMs were explored and some critical facilitating technologies were introduced [e.g., a Network Common Data Form (NetCDF) protocol for defining output variables and metadata, Assistance for Land-Surface Modelling Activities (ALMA); see Table 1], along with a common land surface coupler (Polcher et al. 1998), PILPS could not resolve the full spectrum of land surface challenges alone.

Growing in part from the International Satellite Land-Surface Climatology Project (ISLSCP), an effort was launched to derive 2 yr of near-surface atmospheric forcing *globally* over all land surfaces except Antarctica (Meeson et al. 1995). The data were produced at a 1° spatial resolution and were combined with observational datasets and global analyses from a global weather model to resolve the diurnal cycle. The Global Soil Wetness Project Phase 1 (GSWP-1; Dirmeyer et al. 1999) used the ISLSCP global data to drive LSMs in a framework similar to how they are used in weather and climate models. GSWP-1 was, in one sense, a global implementation of the point-based PILPS evaluations. However, it also had the aim of generating specific products of value. The gridded global atmospheric forcing datasets were technically challenging to develop, and many individual modeling groups found handling the quantity of data and performing the global simulations demanding. However, GSWP-1 was revolutionary in allowing a truly global evaluation of LSMs, encompassing all climate zones and capturing some degree of interannual variability. Comparison of basin-averaged hydrology highlighted the importance of high-quality rainfall forcing in order to simulate correctly the net discharge of water from land to the oceans (Oki et al. 1999). Soil wetness datasets produced in GSWP-1 were used in retrospective forecasts of seasonal climate to show that interannual variations of the land surface state have a significant impact on climate prediction (e.g., Dirmeyer 2000; Douville 2002).

Table 1. Overview of GLASS projects.

Acronym	Expansion	Reference(s)
PILPS	Project for Intercomparison of Land-Surface Schemes	Pitman et al. (1993) and Chen et al. (1997)
GSWP	Global Soil Wetness Project	Dirmeyer et al. (1999, 2006)
ALMA	Assistance for Land-Surface Modelling Activities	www.lmd.jussieu.fr/~polcher/ALMA
GLACE	Global Land Atmosphere Coupling Experiment	Koster et al. (2004, 2009)
LDAS	Land Data Assimilation System	Rodell et al. (2004)
LUCID	Land-Use and Climate, Identification of Robust Impacts	Pitman et al. (2009)
LoCo	Local coupling	Van den Hurk and Blyth (2008)
PILDAS	Project for Intercomparison of Land Data Assimilation Systems	—
PALS	Protocol for the Analysis of Land Surface models	www.pals.unsw.edu.au

Both PILPS and GSWP-1 were critical in bringing the LSM community together, one primarily at the point or catchment scale, and the other at the global scale. However, in isolation neither had the capacity to put their respective contribution into the larger perspective or spectrum of terrestrial processes spanning the point scale with uncoupled simulations to the global fully coupled simulations.

To address this challenge of a more holistic program around land surface processes, GLASS was launched in 1999 and was led by a panel tasked to accelerate the progress made by PILPS and GSWP-1. This panel continued these projects. GSWP was led into a second phase (GSWP-2), a dramatically extended research program covering a 10-yr period (Dirmeyer et al. 2006). GSWP-2 used a range of LSMs, numerous gridded forcing datasets, and a set of evaluation criteria as part of the protocol.

The results of GSWP-2 revealed that the variability in estimated global and annual mean evaporation over land from the participating LSMs is still considerable, and is in fact not a great deal smaller than the range in estimates one can find in the literature back to the start of the twentieth century (Schlosser and Houser 2007). The spread between LSMs can be understood from the fact that over time a wide range of LSMs have been developed for different host models: integrating these models outside of their native environments reveals different sensitivities to the common forcings. However, the projects have provided improved estimates of the typical interannual variability in land surface states and fluxes, uncertainties in observational datasets and reanalyses, climate-dependent model sensitivities, and regional energy and water balances. GSWP-2 also generated a global archive of "realistic" land surface states and fluxes that are used to evaluate the contribution of land processes to atmospheric and hydrologic variability. A thorough review of GSWP is given by Dirmeyer (2011).

To date, this discussion has reflected on LSMs uncoupled from a host model. A critical goal of GLASS was to expand from the uncoupled (or "offline") point-based (PILPS) and globally based (GSWP) evaluations to include simulations that are fully coupled with the atmosphere. Coupled simulations can include LSMs that are either fully integrated into a weather forecast or climate model or coupled into a common mesoscale atmospheric model (Santanello et al. 2009).

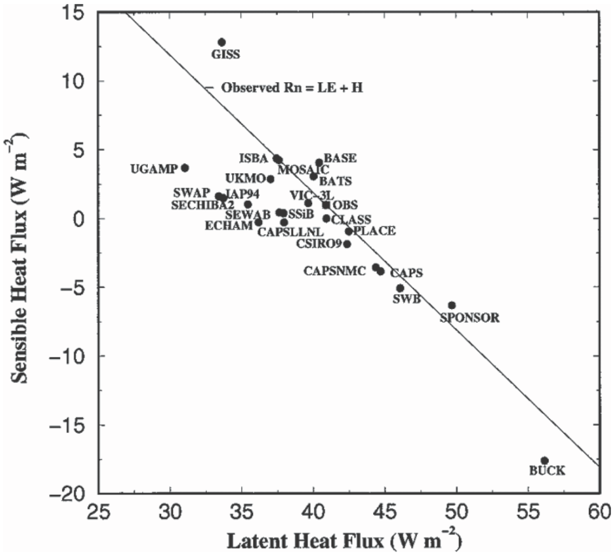

Fig. 1. Example of PILPS scatterplot (from Chen et al. 1997).

The essential contribution to date from the global coupled analysis relates to the Global Land Atmosphere Coupling Experiment (GLACE), a program of research led jointly with the Climate Variability (CLIVAR) panel of WCRP. GLASS helped formulate GLACE, which led to the fundamental discovery by Koster et al. (2004) that LSMs interact with their overlying atmospheric models with remarkably different coupling strengths. In some areas and under some conditions, the state of the land surface systematically affects the atmospheric variability, particularly temperature and rainfall. In the first GLACE experiment, highly controlled seasonal simulations with a dozen different weather and climate forecast models were conducted. The experiment was designed to isolate and quantify the impact of the land surface state, namely, soil wetness, on boreal summer climate variability. For the first time a multimodel map was produced showing areas where land–atmosphere interaction has the strongest effect on precipitation variability (Fig. 2). The considerable spread in this "coupling strength" between the models is often used to illustrate the lack of understanding of this complex coupling process. However, the overall picture that strong sensitivities appear in transitional climate regimes (between arid and humid regions) can be understood from basic physical arguments: near strong gradients of surface evaporation and precipitation, changing the link between soil moisture, evaporation, and precipitation is likely to change the precipitation variability. In the recent follow-up experiment GLACE-2 (Koster et al. 2010), the practical implication of this finding was examined by assessing the contribution of realistic land initial conditions to the prediction of precipitation and temperature. This new multimodel experiment demonstrated that increased skill can be expected on time scales beyond deterministic atmospheric

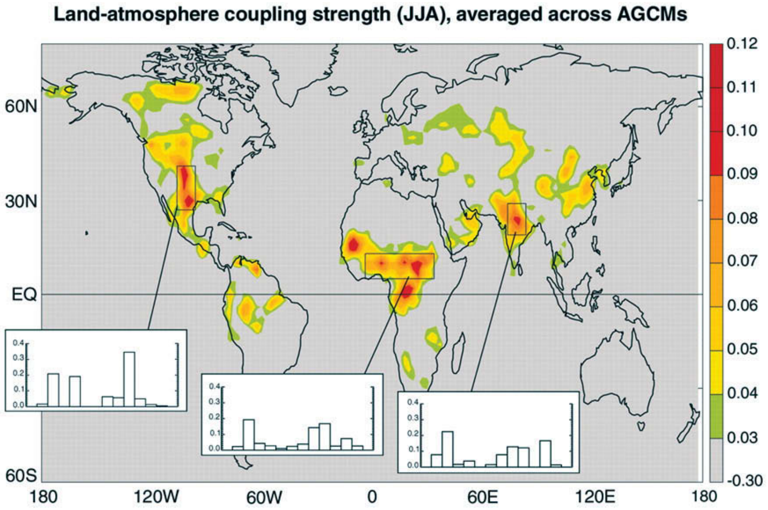

Fig. 2. Land–atmosphere coupling strength diagnostic (dimensionless) between modeled soil moisture and precipitation, determined in the GLACE experiment (Koster et al. 2004). [Reprinted with permission from AAAS.]

predictability (about 2 weeks) out to time scales where ocean–atmosphere interactions become the dominant forcing of climate variations (about 2 months). Forecast skill increases particularly in areas where the precipitation observations used to generate the initial soil moisture states (obtained from GSWP-2) are of high quality and gauge density. Also, it was found that stronger initial soil moisture anomalies lead to larger skill improvements.

To complement the global and seasonal climate focus of GLACE, the issue of land–atmosphere coupling at the process level (i.e., from local to regional) is systematically being addressed in the local coupling ("LoCo") theme (Van den Hurk and Blyth 2008). Land–atmosphere interactions are present at all scales. For instance, the atmospheric properties within a plant canopy directly change in response to fluxes to and from individual leaves. The atmospheric boundary layer feedback reduces evaporation from the surface after being moistened by earlier evaporation. Convection can be triggered by soil moisture anomalies, thereby reinforcing or reducing these very same anomalies (see Seneviratne et al. 2010). Because of this complex hierarchy of processes, and the strong interaction with ambient atmospheric conditions, a straightforward experimental design to systematically evaluate the degree to which land surface processes affect the atmosphere locally is not easily realized. However, a continuous scientific discussion engaged by a series of GLASS workshops led to an experimental protocol using a numerical land–atmosphere model "laboratory" where a wide range of land, boundary layer, and cloud models can be interchanged and subjected to meaningful diagnostics under controlled conditions [Land Information System–Weather Research and Forecasting (LIS–WRF)]. Newly developed diagnostics address the scale dependence and various natures of land–atmosphere feedback, and they include a combination of land and atmospheric variables (Santanello et al. 2009). LoCo is an example of a GLASS project where a fairly long incubation time was needed before a practical experimental design could be formulated (the first LoCo workshop was held in 2003); however, it will transform the ability of LSMs to realistically represent not only the fluxes and states, but also the complex interactions and feedbacks with the atmosphere. Inputs to these workshops were provided by colleagues from the GEWEX panels on boundary layers [Global Atmospheric Boundary Layer Study (GABLS; online at www.gewex.org/gabls.htm)] and clouds [Global Cloud System Study (GCSS; online at www.gewex.org/gcss.html)].

An important aspect of land modeling is the specification of the land surface characteristics and their temporal and spatial variability. The importance of this implementation is convincingly demonstrated by a recent study addressing the impact of land use change—the Land-Use and Climate, Identification of Robust Impacts (LUCID; Pitman et al. 2009). LUCID was a GLASS–Integrated Land–Ecosystem–Atmosphere Process Study (iLEAPS; online at www.ileaps.org/) in which seven GCMs were given a similar land use change scenario. A large part of the variability of the regional climate impact of land use change could be attributed to different assumptions on the change of LSM parameters associated with the imposed land use change. A systematic protocol to objectively assess the sensitivity of surface fluxes to the specification of canopy conductance, leaf area index, surface roughness, and rooting depth is not easily defined, resulting from the fact that these quantities are strongly intertwined with the core LSM structure. However, the current development of GCMs into sophisticated Earth system models (incorporating the biogeochemical cycles associated with the biotic components of our climate system) warrants a careful analysis of the role of these land surface characteristics.

Since the inception of GLASS, the scientific LSM arena has seen rapid evolution. PILPS-type experiments have become integrated into land surface model development and diagnostics, and are now commonly performed for an expanding number of climate regimes and land-related process areas. Model-based global estimates are now being considered as a valuable component of climatologies of the land surface states and fluxes, demonstrated by activities around the LandFlux (http://wgdma.giss.nasa.gov/landflux.html) initiative, coorganized by the GEWEX Hydroclimate Panel (GHP; online at www.gewex.org/projects-ghp.html). Land Data Assimilation Systems (LDASs; Rodell et al. 2004) have been modeled after the GSWP framework, and all of the operational LDASs as well as most land surface intercomparison projects use the ALMA protocols. GLACE-like procedures and metrics are adopted in quite a few studies addressing land–atmosphere interaction, including changes in the patterns under future climate conditions (Seneviratne et al. 2006). Recognizing the importance of uncertainties in prescribed model parameters for model results and data assimilation products, parameter estimation tools and associated forecast evaluation diagnostics have been implemented in Land Information System (LIS; available online at http://lis.gsfc.nasa.gov). However, the overarching questions—how good should our land models be?, how accurately can we estimate land variables on a global scale?, or how large is the inherent climate predictability related to land?—still require new scientific approaches.

In this changing landscape, GLASS has recently restructured its scientific agenda, and is currently in the process of launching new concepts and experimental designs aimed at progressing land surface science. The original structure of GLASS was a two-by-two matrix, where one axis represented spatial scale (point/plot/catchment versus continental/global) and the other differentiated between uncoupled and coupled modeling. In the new structure, three core activities have been defined: benchmarking, model data fusion, and coupling (Fig. 3).

Benchmarking of LSMs (and datasets) urgently needs attention in the wider scientific community. Do we actually know what we can expect from the quality of models and datasets? In an inspiring experiment, Abramowitz et al. (2008) evaluated the skill of an LSM driven by and evaluated with data from a number of flux network (FluxNet; available online at http://daac.ornl.gov/FLUXNET/fluxnet.shtml) sites. Apart from the land models, an unrelated statistical model was calibrated on a subset of the observed forcings, and evaluated with an independent subset. In many ways, this statistical model considerably outperformed the state-of-the-art LSM simulations. This result leads to the conclusion that the complex physical equations embedded in the LSMs did not utilize the information content inherent in the forcing data well. These equations typically have many parameters, few of which can be practically optimized for most locations. For an LSM to be useful for predictions, it must be demonstrated that the model physics actually adds information to the prediction system. Thus, in our model evaluation experiments we should reduce model errors to a minimum, but also specify what the minimum acceptable error actually is. Obviously this depends on the application of the model. For example, a flood forecasting center only using modeled runoff to predict the occurrence of floods in a river basin has a different definition of the minimum acceptable error than scientists trying to attribute trends in evaporation to soil moisture processes (Jung et al. 2010). A general benchmark for models could be that they are able to capture a useful mode of variability (e.g., interannual variability, or match the error level of the validation observations), but more specific benchmarks need to be developed. GLASS seeks ways to engage and formalize this process. A good showcase for this is the proposed third phase of GSWP (online at http://hydro.iis.u-tokyo.ac.jp/HESSS2/), in which the earlier GSWP-2 datasets will be extended forward to the present, enabling scientific progress toward attribution of recent changes to various components of the climate system, including

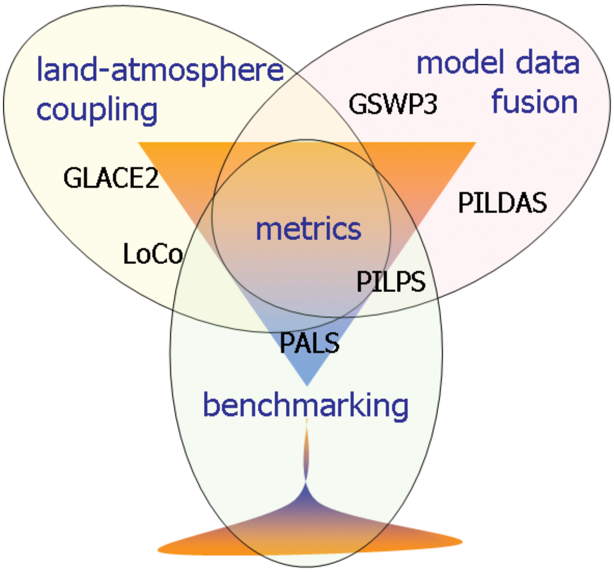

Fig. 3. Layout of new GLASS structure.

the terrestrial component. The development of the web-based Protocol for Analysis of Land Surface Schemes (PALS; online at www.pals.unsw.edu.au/) will help for an objective definition of useful benchmarking standards.

The activities clustered around model data fusion address the need to gain experience in the areas of data assimilation and parameter estimation. In various scientific arenas surrounding the land modeling domain (numerical weather prediction, catchment hydrology, and ocean science), data assimilation is a common tool to estimate optimal states of the climate system by blending observations with models constrained by physical equations. Also, the notion that model parameters should show larger variability leads to a rethinking of the concept of fixed land models that are driven by fixed atmospheric forcings. However, data assimilation techniques are conceptually simple but mathematically quite complex, and small changes in the underlying error assumptions can lead to large differences in the results. A newly formulated Project for Intercomparison of Land Data Assimilation Systems (PILDAS) is a first attempt to learn how configuration differences among a number of current operational land data assimilation systems affect the resulting estimates. Like the early PILPS projects, PILDAS contains a hierarchy of levels with subsequently increasing numbers of degrees of freedom. In the first pilot phase, a synthetic (model produced) dataset will be assimilated in a range of configurations. Ultimately PILDAS will address consequences of choices of data types, ways of preprocessing data, and technical settings, such as length of assimilation windows, spatial correlations, and error structure. Results from the first PILDAS phase will appear in 2012.

The coupling theme will continue the earlier work related to GLACE and LoCo, concentrating on the development of adequate diagnostics for land–atmosphere coupling that can be verified with observations and the use of standard modeling software (LIS), where model settings can be easily controlled and evaluated. Pilot experiments are currently ongoing, and a call for participation from the broader community can be expected over the next few years. It should be noted that the GLASS themes are certainly not independent, and activities in benchmarking and model data fusion will need to be considered in both uncoupled and coupled frameworks.

During its existence, GLASS activities have strengthened and created many scientific networks, leading to scientific progress. Reflecting WCRP's emphasis to contribute to operational modeling centers, the National Centers for Environmental Prediction (NCEP), Japan Meteorological Agency (JMA), Met Office (UKMO), Météo-France, and European Centre for Medium-Range Weather Forecasts (ECMWF), among others, have used GLASS activities to improve their forecast models. For example, results from PILPS-2E by Van den Hurk and Viterbo (2003) have been formally included in the ECMWF model by Balsamo et al. (2009). De Rosnay et al. (2009) explore LSM-generated soil moisture fields in West Africa to prepare for routine assimilation of Soil Moisture Ocean Salinity mission (SMOS) data. Routine application of LDAS products is used in operational forecasts of NCEP and other centers worldwide. Building on earlier successes, GLASS will continue to support projects that extend the earlier frameworks, like GSWP-3 or ongoing or new PILPS-like experiments, and renew its focus on emerging topics like model data fusion and benchmarking. As before, GLASS will coordinate workshops, model studies, and analyses in order to strengthen or create the scientific networks that are needed to bring the representation of value-adding land surface modules in Earth System Models to a higher level.

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QUALITY ASSURANCE IN ATMOSPHERIC MODELING

BY THOMAS T. WARNER

The rapid growth in the number of atmospheric model users is motivation for reviewing best practices in atmospheric modeling and emphasizing the scientific and technical preparation that is necessary to use the modeling tools effectively.

A formal definition of quality assurance that is applicable to this discussion is as follows: the maintenance of a desired level of quality in a service or product, especially by means of attention to every stage of the process of delivery or production. A lack of such quality assurance in the atmospheric modeling process can result from many causes. One is that some model users are less well trained and less experienced than others and lack an appreciation of the sensitivity of model solutions to the numerous decisions that must be made when configuring a model for a particular application. Another is that demands for quick results can lead to a less-than-thorough model setup and verification. A related factor is the availability of state-of-the-science community models; this represents a great potential benefit to the community, but there is the risk that the models will not be used wisely. This paper suggests ways in which the atmospheric modeling process and culture can be improved, and it is aimed especially at the many novice modelers who are using these tools. The recommendations apply to the use of models for operational forecasting of weather,[1] for climate prediction, for research-oriented case studies, and for the generation of reanalyses. Many of the suggestions are not new ones, having appeared decades ago in references such as Anthes (1983) and Keyser and Uccellini (1987). This paper merely collects the wisdom from these and other sources and includes some additional contemporary advice. Note that there is no attempt here to provide a complete list of references for the discussion topics; the reader should refer to a text on numerical weather prediction (NWP) for this information.

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

DOI:10.1175/BAMS-D-10-00054.1

In final form 18 May 2011

THE INCREASING USE OF ATMOSPHERIC MODELS. Thirty years ago, atmospheric models were used primarily by research scientists at government and university laboratories and by national

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[1] In addition to the large operational forecasting centers, many universities, commercial organizations, and individual countries run models in real time for research, forecaster training, and operational prediction.

weather services for operational prediction. The small cadre of model users had degrees in atmospheric sciences and almost certainly had benefited from formal courses in NWP. Since that time, many factors have contributed to a rapid increase in the number of model users and in the diversity of their scientific and technical preparation. These factors include the following:

- easy access to turn-key community models;
- the ease with which models can be applied, as facilitated by the use of graphical interfaces, online documentation, and training courses;
- rapidly declining costs and increasing user friendliness of high-performance computing and data-storage hardware;
- the increasing accuracy of models, when used properly;
- a greater awareness of the value of model-generated weather and climate information;
- the greater maturity of coupled secondary models that allow forecasts of atmospheric variables to be used for prediction of floods, infectious-disease outbreaks, electric-power consumption, air-quality-related health warnings, etc.;
- the realization by nearly every nation that it is being affected by climate change and the resulting desire to perform climate downscaling to answer practical questions about future water resources, agricultural productivity, etc.;
- the—perhaps unfortunate—growing expectation by reviewers of grant proposals and journal submissions that models should be a part of most research studies;
- the use of atmospheric models by specialists from other scientific disciplines; and
- the maturation of science in some developing countries.

An example of the increase in the number of users of two particular community models is shown in Fig. 1. The fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) was a community modeling system that was replaced by the Weather Research and Forecasting model (WRF). The ordinate in the figure is the number of subscribers to an e-mail-based news system that supports model users. Because users typically unsubscribe when they are not using the model, the number of subscribers is arguably proportional to the number of active users at any time. Clearly there has been rapid growth, especially over the last half decade, in the number of users of the WRF. This number is almost certainly an underestimate of the actual number of users (every user does not subscribe, but it is unlikely that nonusers subscribe), so the focus should be on the growth rate. The rapid increase in the number of users that is illustrated in this example and that is a result of the above-listed causes is motivation for reviewing best practices in the modeling process. Note that this increase in the number of WRF users may partly be a result of users switching from other models, but there is anecdotal evidence of growth in the number of users of other community systems, such as the Consortium for Small-Scale Modeling (COSMO) model.

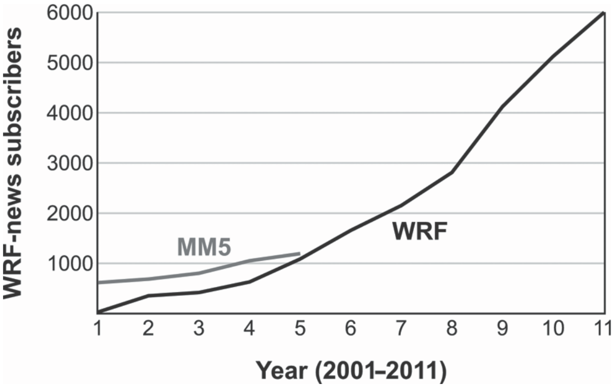

Fig. 1. An example of the increase in the number of users of two particular community models as a function of year. MM5 was a community modeling system that was replaced by the WRF. The ordinate in the figure is the number of subscribers to an e-mail-based news system that supports model users.

REASONS WHY BEST PRACTICES ARE SOMETIMES NOT FOLLOWED IN THE MODELING PROCESS. An increase in the number of model users cannot itself be responsible for the misapplication of models. However, there are many related factors that are causative. For example, new users may come from atmospheric science departments that do not offer an NWP course. Without the benefit of this course, they have to resort to learning best practices through self study, through trial and error, or from more skilled colleagues. This is a significant problem because models are complex and imperfect tools and their shortcomings should be understood well by every model user. An even more unfortunate situation is one in which model users, in addition to having no NWP training, have no background in atmospheric sciences. This means that they are less likely to recognize when a model solution looks meteorologically unreasonable, because of either basic model deficiencies or improper model settings. As evidence of this situation, about one-half of the applicants for a recent tutorial on the use of a mesoscale model had no formal training in NWP and about one-fourth had little or no atmospheric science background. Finally, in addition to this lack of training as a problem, time and financial pressures experienced by some model users sometimes prevent them from carefully applying the models, even if the expertise exists to do so.

STEPS FOR IMPROVING MODELING PRACTICES. Most model users adhere to some of the following good practices, but often steps in the process are omitted in order to save time or because the user is unaware of the importance of the step. This is not a complete list of all the steps in a model application, but rather they are important ones that are often neglected or given insufficient attention.

1) Clearly define the scientific or practical objective. Too often, the model configuration is determined and experiments are performed without first writing down the specific questions to be answered, the expected results, and how the results will be used. As obvious as this step seems, project objectives are often not well defined and articulated from the start, and as a result model configurations must be modified and simulations rerun after goals becomes clearer with time. In fact, a careful definition of the objectives may lead to the conclusion that an analysis of the observations alone, without the use of a model, may be the best and most efficient approach.
2) Based on the above-defined objectives of the modeling project, identify and develop a physical understanding of the atmospheric processes that must be accurately simulated. This information about relevant physical processes will be essential for making decisions about model configuration, such as the necessary vertical and horizontal resolutions, and the most appropriate physical process parameterizations. It is also necessary in order to calculate the accuracy of the model relative to particular processes or variables of greatest importance. If the model is for general-purpose weather prediction, a variety of processes may be important. In contrast, some models have a narrowly defined goal: for example, for use in predicting electricity demand over a local area, in which case processes that control cloud cover and near-surface temperature would be especially critical. This step can involve a significant time investment in observational-data analysis if the model is being applied in a region where the atmospheric processes have not been previously well studied. Otherwise, it will simply entail a careful analysis of the research literature. Without this step, many subsequent decisions (e.g., about model resolution) in the process will be made arbitrarily and quite possibly incorrectly.
3) Perform a thorough analysis of all available observations. Modelers should remember the often forgotten concept that there are three complementary approaches for studying the atmosphere, involving the use of observations, models, and theory (Hoskins 1983). The user should quality check and study all observations for the proposed simulation period of case studies used for research and for testing model improvements. Using the observations alone, one should perform the best possible overall analysis of the vertical and horizontal structures of the prevailing processes; this could require considerable time. Any conclusions from a study that involves the use of models will be much stronger if a thorough analysis of observations and the use of theoretical concepts are also part of the process. If the modeling is part of a doctorate dissertation, then in some cases it would not be unreasonable to spend a significant number of months just analyzing the observations, before touching the model. This is a justified investment in time, which will improve research efficiency and strengthen the outcomes.
4) Prepare an experimental design. This design should describe the model runs (not necessarily the configuration) that will be needed to accomplish the previously defined objectives. If case studies are being used, how many will there be and how will cases/dates be chosen? Will there be physical process sensitivity studies, and, if so, how will the solutions be compared (e.g., through simple subtraction of solutions or through the use of more complex methods)? Will the verification of the model solution be subjective or objective (statistical)? Specific aspects of the model configuration are defined in later steps, but preparation of this design ensures that the overall process has been thought through. Of course, with research there will inevitably be midcourse corrections in the design as the work progresses. The time required for preparation of the experimental design will depend on the experience of the model user.

In addition to the possibility mentioned in step 1, that the experimental design may include only an

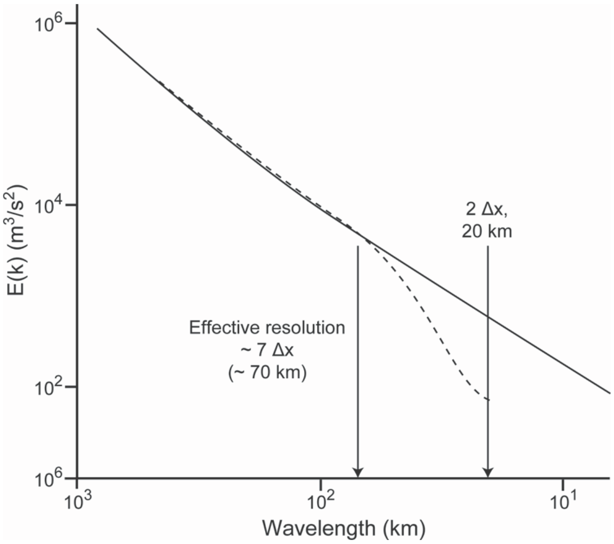

Fig. 2. The influence of explicit and implicit model diffusion on the kinetic-energy spectrum for a WRF forecast having a 10-km grid increment. The expected slope of $k^{-5/3}$ is shown as a reference and is reproduced by the model for wavelengths greater than 7Δx. However, the energy between the 2Δx and 7Δx wavelengths has been damped by the model diffusion, resulting in an effective resolution of 70 km, not 20 km (2Δx) (adapted from Skamarock 2004).

analysis of the observations and no modeling, an additional design decision is whether to use real-data or idealized simulations. Even though real-data simulations are more common, for some project goals it may be more appropriate to use idealized (i.e., synthetic) experimental conditions. Here, the initial conditions and the forcing (e.g., land surface) are defined based on a simple conceptual model, and the model results are much easier to interpret because many processes are not interacting, as will be the case with real-data simulations. Some community models, such as the WRF, have options for using a variety of preconstructed, idealized, test cases, such as for flow over a mountain, a squall line, etc.

5) Define the required horizontal and vertical resolutions of the model, based on knowledge of the typical length scales of the (above established) specific processes that must be simulated well. If air quality in a coastal city must be simulated, then boundary layer processes associated with the land–sea breeze and urban-heat-island circulations will be important. This knowledge would guide the user to perhaps employ i) more model layers within the lowest 1–2 km above the surface in order to resolve the shallow, thermally driven boundary layer circulations and ii) high horizontal resolution to allow simulation of the mesoscale sea-breeze front. The estimate of the required vertical and horizontal grid increments should be based on knowledge of the "effective resolution" (Skamarock 2004) of the specific configuration of the model being used. That is, a number of aspects of a model configuration (e.g., the amount of explicit and implicit diffusion) control the filtering of the model solution. The resolution should be chosen such that all physical processes that are relevant to the study are adequately rendered by the model. Figure 2 shows the effective resolution for one configuration of the WRF, which has less smoothing than many models. Here, the effective resolution is ~7Δx in the context of the kinetic-energy spectrum. Other configurations (e.g., the specified magnitude of the coefficient for the explicit diffusion and the order of the diffusion) of the same model would result in a different effective resolution. Obviously, computational limitations exist for every project, so an outcome of this analysis may be that it is not feasible to accomplish the stated objective with the available time and computing hardware.
6) Avoid the tendency to prematurely run the model, before the above-listed steps have been completed. Model users very often prematurely begin running the model, imagining that this will lead to an earlier completion of a project. In fact, this leads to inefficiency in the process, wasting time and computing resources, because model simulations will inevitably need to be rerun. The author's experience is that, the sooner that the model is run, the longer a study will take. Avoiding the temptation to run the model before thoroughly understanding the prevailing meteorology, before defining the experimental objectives and design, etc., is simply a matter of willpower.
7) Choose the model start time and the method of model initialization to allow for spinup of the physical processes of interest. Many model users do not realize that, depending on the initialization method and the prevailing physical processes, the model may need time to spin up clouds; precipitation; local ageostrophic circulations, which are associated with orographic or coastal forcing; and boundary layer structure. With some data assimilation methods, this might be enabled by running the model for several data assimilation cycles before using its output. Some methods, such as variational assimilation, may require considerable understanding and time in order to properly define information such as

background and observation error statistics, and they may thus be less attractive for inexperienced users. In contrast, many model users simply throw away the first few hours to one day of the simulation due to spinup issues, before using the model output, but this allows time for error to accumulate. The model start time relative to the study period is also a consideration. For example, when performing a modeling study of the daytime boundary layer, the initialization time of the model can greatly affect the results. Should one start the model the night before the study day, the morning of the study day, or the morning of the previous day to include the residual boundary layer and larger-scale effects from the previous day? Performing sensitivity experiments and reviewing the literature to assess what has worked in other studies is always a good idea.

8) If a limited-area model (LAM) is being used, then run test simulations to evaluate the sensitivity of the model solution to the computational domain size (i.e., lateral boundary location). The solutions from LAMs are notoriously sensitive to the locations of the lateral boundaries, and the use of excessively small domains often results in large errors. Tests should be conducted to define the optimal locations of the boundaries. The lateral boundary problem can take the form of a LAM, with two-way-interacting nested grids, that is parasitically (one way) nested within a coarser (e.g., global) model, or a single-grid LAM can be parasitically nested within the coarser grid. If a single case is being studied, perhaps five simulations will be sufficient to define the sensitivity of the model solution to lateral boundary location, as well as the configuration that produces the best verifying solution. If the model is to be used for general-purpose operational NWP, each lateral boundary configuration should be tested for a range of weather regimes, flow patterns, and seasons, and a compromise solution should be found for the lateral boundary location. This process could possibly involve over 50 simulations, but this investment is arguably reasonable when establishing an operational modeling system.

Figure 3 shows a jet streak simulated by two versions of a LAM. One simulation (Fig. 3a) employed lateral boundaries that were located a long distance from the geographic area of interest (shown in the figure) and the other (Fig. 3b) had the lateral boundaries located at the edge of the area shown in the figure. The narrower jet streak in Fig. 3a is more realistic, as confirmed by radiosonde observations. In both cases, the lateral boundary conditions were provided by the same coarser-resolution global model. When there is flow over complex orography (exciting vertically propagating gravity waves), different options, if available, for upper-boundary conditions should also be tested.

9) Using sensitivity studies and reviewing the literature, define the most appropriate physical process parameterizations based on the geographic area, the available observations, the horizontal and vertical grid resolutions, and the processes being simulated. Community models often allow a user to select from a list of available parameterizations for convection, radiation, land surface processes, cloud microphysics, and boundary layer turbulence. The user should evaluate the sensitivity of the model solution to the choices of

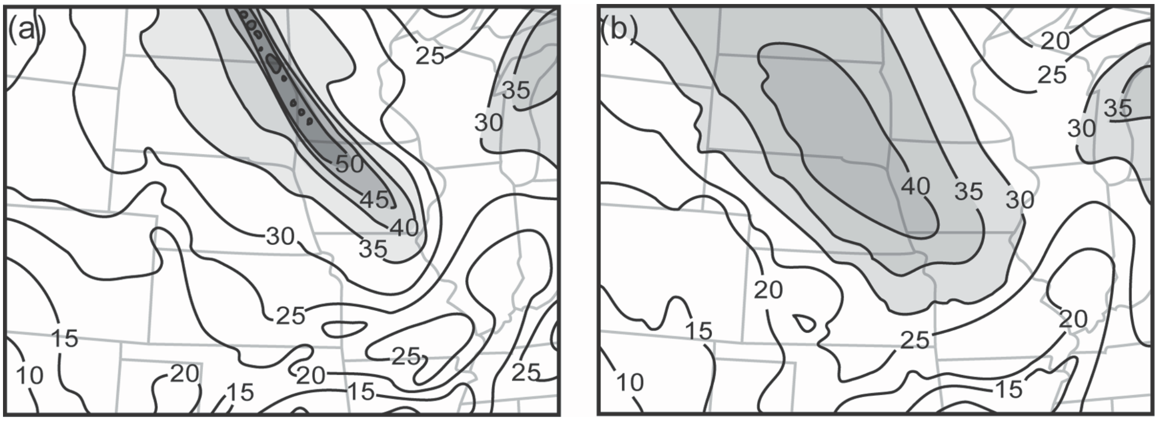

Fig. 3. Shown are 12-h simulations of 250-hPa winds (m s^{-1}) from the 40-km grid increment Eta model initialized at 1200 UTC 3 Aug 1992, based on experiments that used (a) a large and (b) a small computational domain. The isotach interval is 5 m s^{-1} (from Treadon and Petersen 1993).

> parameterizations. This is necessary because the performance of parameterizations can depend on season, the grid increment, the availability of observations, and the meteorological processes that prevail in specific geographic regions. This is why textbooks and model documentations do not attempt to suggest “the best option,” something that users often desire. The “default” parameterizations suggested in the user documentation for a particular modeling system will not necessarily provide the best model simulation. Note that, when a model does not produce the desired solution, a common practice is to blindly try different combinations of parameterizations, without attempting to understand the reasons for poor model performance. Ideally, the user should investigate the assumptions inherent in the parameterizations and better understand the reasons for a particular pattern of errors (see Stensrud 2007). This will reduce the chances of getting a right answer for the wrong reason.

How the availability of observations can influence the choice of parameterizations can be easily understood in the context of land surface process parameterizations. In particular, using a complex land surface process model that requires the specification of many properties of the substrate and vegetation may result in a worse simulation than would be obtained from a simple model, if the land surface properties are only poorly observed for the geographic area being modeled.

The list of parameterizations to be tested can be shortened based on a literature review of what has worked best in other model applications for the region. However, if the model grid increment is markedly different than those used in other studies, the parameterizations might need to be retested. Also, newer available parameterizations whose performances have not been thoroughly described in the literature should also be evaluated.

The potential dependence of a model solution on the choice of a parameterization is shown in Fig. 4 in terms of the sensitivity of the accuracy of precipitation forecasts to the choice of the convective parameterization. The rainfall rate is plotted for a spring-season convective event (Fig. 4a), from observations, from four simulations that used different well-known parameterizations for convection, and from one simulation that used no parameterization for convection. At specific times in the simulations, the rainfall rate varied by as much as a factor of 4 among the different parameterizations. Also depicted is the bias score averaged for three warm-season convective events (Fig. 4b), again for each of the four parameterizations and for the use of no parameterization. Both the simulation-average scores on the right, as well as the time-dependent curves show a substantial dependence of the simulated precipitation amount on the parameterization that was employed. If one were to analyze the simulations of these cases in order to determine the best parameterization for convection, then it would be appropriate to go beyond the statistics shown and look at various object-based

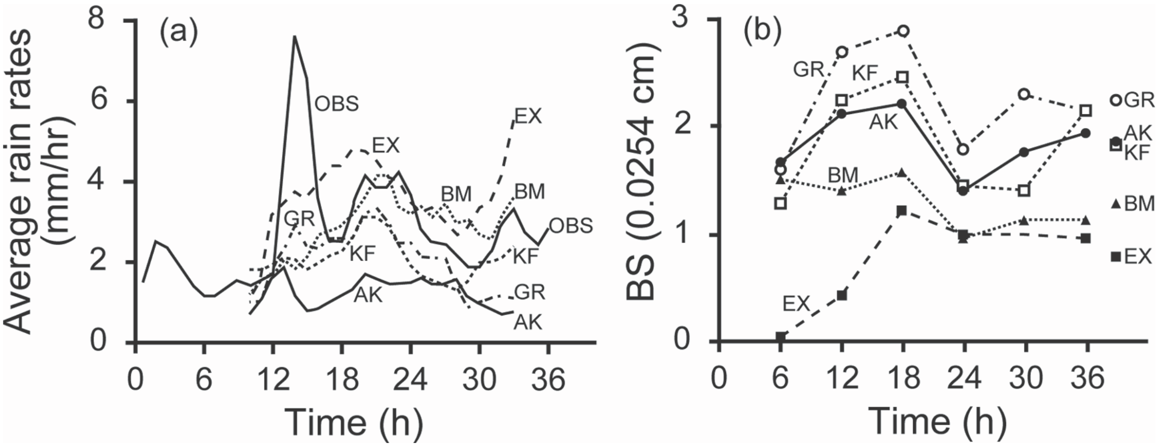

Fig. 4. (a) Average rainfall rate, for a spring-season convective event, based on observations (denoted as OBS) and for five simulations that used different treatments for the convection: four different parameterizations and no parameterization (denoted as EX). (b) Also depicted is the rainfall-rate bias score averaged for three warm-season convective events, again for each of the four parameterizations and for the use of no parameterization. The four convective parameterizations were the Grell (GR), Kain–Fritsch (KF), Betts–Miller (BM), and Anthes–Kuo (AK) schemes (adapted from Wang and Seaman 1997).

metrics such as the size and intensity distribution of the observed and simulated convective elements.

Finally, note that some combinations of parameterizations should be avoided, for example, because one parameterization can require the availability of specific variables from another parameterization. Good model documentation should alert the user to such situations, or the software might even prevent such choices from being made. However, when the documentation is insufficient, it is the user's responsibility to understand the parameterizations well enough to define any incompatibilities. Unfortunately, there is no good summary of these ill-advised combinations.

10) Understand the limitations to the predictability of the phenomena being modeled. Although estimates of inherent predictability limits for various phenomena are only guidelines, unrealistic expectations of the ability of any model to predict features of interest may result in i) erroneous conclusions about a model's predictive ability (or lack thereof) or ii) excessive time spent trying to tune a model to produce a particular solution that is exceptionally sensitive to any aspect of the model setup (e.g., initial conditions). The experimental design should recognize the limits of predictability; for example, should the model evaluation be purely statistical (e.g., does the model produce the right number of hurricanes per year) or deterministic (e.g., does the model produce a realistic evolution of a particular storm)? Of course, to a large degree our expectations about the predictability of various phenomena must be based on the configuration (e.g., resolution) of the model being used. Discussions of predictability limits for different atmospheric phenomena can be found in a number of NWP books, which should be consulted to ensure that there are realistic expectations about model capabilities. Finally, ensemble methods allow for a better assessment of the predictability of a process, compared to the use of a single deterministic run.
11) Establish a verification plan before the model is run and perform a thorough verification, using appropriate metrics, of the model solution using all available observations. The objective and subjective verification of model forecasts or simulations is essential for a variety of reasons. The following list is from Warner (2011):

- Most models are under continuous development, and the only way users and developers can know if routine system changes, upgrades, or bug fixes improve the forecast or simulation quality is to objectively and quantitatively calculate error statistics.
- For physical process case studies, where the model is used as a surrogate for the real atmosphere, the model solution must be objectively verified using observations, and, if the observations and model solution correspond well where the observations are available, there is some confidence that one can believe the model in the space and time gaps where there are no observations. This is a necessary step in most physical process studies.
- When a model is being set up for a research study or for operational forecasting, decisions must be made about choices for physical process parameterizations, vertical and horizontal resolutions, lateral boundary placement, etc. Objective verification statistics are employed for defining the best configuration.
- Only through verification does a forecaster have any chance of developing a sense of a model's systematic weaknesses and how to compensate for them. If the human wants to be in the loop and add value to a model forecast, then this is a requisite step.
- Objective decision-support systems that utilize atmospheric model forecasts as input can benefit from information about the expected accuracy of the meteorological input data.

A verification plan should be established before the model is first run, for a variety of reasons, including the fact that the selection of output frequency and output variables can depend on how the data will be used in the verification process. The verification plan should include the following information:

- Define the variables that will be the focus of the verification process. For general-purpose NWP, all variables may be equally important. When models are being used for a specific purpose, verification of particular variables will be emphasized. For example, for power companies, accurate forecasts of rapid ramp ups and ramp downs of wind speed at ~100 m above ground level are critical for efficient integration of wind power with other energy sources, so these events would be a focus of the verification.
- Describe the verification metrics to be used, whether they are feature (event) based or more traditional ones (e.g., bias, mean absolute error). The metrics should be specific and sensitive to

the weather features that are most important to the users of the model products. In the above mentioned example of ramp events, feature-based metrics could quantify the timing and amplitude errors of the forecast ramp events.

- Establish a process for defining the simulation period(s) to be used in the verification. This is an easy step if the model is being used for a research project to study a specific meteorological event. If an operational general-purpose NWP model is being prototyped or modified, the verification process can entail i) the emulation of the operational forecast cycling for a long multiseason period or ii) the simulation of a number of standard test cases/events/periods. One should avoid the natural temptation to choose only extreme weather events for evaluation of model performance; it is also important to evaluate it with more commonly occurring cases.

Most verification of high-horizontal-resolution models entails the use of traditional metrics, such as mean absolute error and root-mean-square error (RMSE), even though the results can be misleading and not necessarily demonstrate the real value of a forecast. See Davis et al. (2006a,b) for a discussion of the sometimes preferable event- or feature-based verification. Figure 5 illustrates a common problem when traditional metrics are used with high-horizontal-resolution models. In this example, model forecasts have both phase and amplitude errors. The solid line represents the observed wind speed in a jet. The dashed line shows a forecast from a model with high resolution, where the correct amplitude of the jet is retained but the maximum is displaced to one side. The dotted–dashed line and the dotted line show forecasts from models that produce a smoother solution. The RMSE of the forecast wind speed will be worst for the model solution that best renders the correct amplitude of the feature.

Performing a good objective verification does not mean that it is unnecessary for the modeler to visually review a wide range of model output variables and assess their general realism. Only through this process can the modeler develop a subjective sense of the model performance and identify error patterns that would not be apparent in the objective performance statistics. This obviously requires a good background in atmospheric science in general and specifically a knowledge of what the atmosphere looks like in terms of analyses of observations (gained from a weather-analysis course) and conceptual models. As a caution, however, using subjective verification in the process of defining the best configuration of a model (e.g., lateral boundary location and parameterizations) involves a risk that the model configuration will be inadvertently "tuned" to produce results that fit the modeler's incorrect understanding or conceptual model of a process.

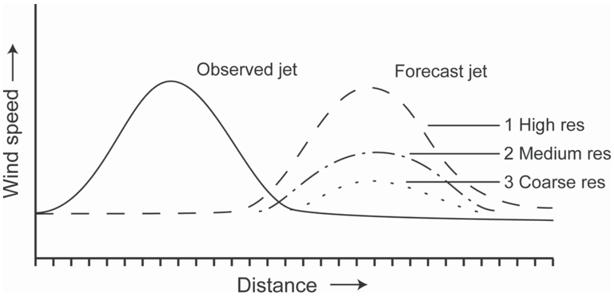

Fig. 5. Illustration of how a smooth forecast can lead to better verification statistics than a forecast with a more correct amplitude in structural features (see the text for discussion; from Warner 2011).

If the verification process shows the existence of errors in the model solution that are larger than those reported in the literature in similar situations (phenomenon, geographic region, and season), adjust the model configuration accordingly (resolution and parameterizations) and rerun the simulations. Inadequate verification is a common and unfortunate compromise that is sometimes made by model users who are in a hurry to complete a project or who have unwarranted trust that the model will always perform well. It is arguably the most important step of all. Although costly, it is difficult to imagine a scenario where a thorough verification does not improve results.

12) Be well organized in maintaining a detailed experimental log and the files of model code and output. The natural tendency is to assume that one will remember the details of a model run or remember to write them down later, but such overconfidence often leads to situations where one is missing key information that would allow interpreting or reproducing the results at a later time. Thus, it is important to record the specifications of each model run immediately in an organized format. The same experiment log can also be used to refer to reference file numbers or names that will allow for retrieval of the specific model code used, and it can be used to record the interpretation of the results. This thorough recording of the conditions of an experiment, numerical or otherwise, is central to the scientific method. A related recommendation is that

a systematic approach be used for organizing digital files on a disk, of model code versions and model output files. Failing to have a well-organized overall process will result in lost time, wasted computer resources from rerunning experiments, and confusion.

13) Use good coding practices and well-documented and well-tested software. Many model users employ publically available models and other supporting software packages without modifying them. However, the availability of such software on the web obviously does not mean that it has been well tested, and this is problematic because every model user is ultimately responsible for the veracity of the software that is used in a research project.

Other model users, however, develop and test new model components as part of research projects, and any coding errors negatively affect the quality of the results, perhaps to an even greater extent than not following the above-listed practices. Developing quality code and adequately testing it is a matter of taking one's time and paying attention to detail. There are two ways of testing code, called black-box and white-box testing. In the former, the code is treated as a black box, and the code output is checked for realism. If a model has been modified, this could take the form of applying standard verification metrics to ensure that errors are within expected bounds, or there are ways in which models can be run for simple idealized situations and the model output can be compared with analytic solutions. Alternatively, white-box testing involves evaluating individual segments of new code in order to ensure that they are operating as expected. Opportunities for developing good coding, code-testing, and code-debugging practices can be provided to students in NWP courses by including a laboratory component that requires them to code and run simple models, perhaps based on the one- or two-dimensional shallow-fluid system of equations.

All publically available models undergo periodic major and minor upgrades, and new releases of the software are made available to the community. A historical example of a major upgrade was the release of the WRF, which eventually replaced the MM5. More often, major upgrades involve the implementation of large new segments of code within the same model, and the minor ones may be aimed primarily at fixing software bugs. This cycle of software releases can present the model user with the need for the following two types of decisions:

- For a new research project, is it better to use the newest major revision of the modeling software or the previous version? Even though the new version usually contains improvements of some sort, it also inevitably contains bugs that will be corrected as it is used in the future. It is recommended here that a new research project not employ a very recently released model or a model with a recent major upgrade, unless the upgrade has involved major bug corrections. Using the new model would involve the risk that a significant bug would be uncovered during a project and the work would need to be redone. Let others rush to use the new model and uncover the bugs.
- For an ongoing research project, should the work be periodically transitioned to new minor releases of the model or should it be completed with the original version? The answer here depends on a number of factors, including whether the release takes place near the beginning or the end of the project, the type of experiments that are being conducted, and whether the new release contains significant corrections to bugs. If the model user is in the middle of sensitivity studies, then of course there should not even be small changes in the software. If significant code bugs are corrected in a release, then it is arguable that experiments should be rerun with the new code or at least model runs should be used to determine whether the code change significantly affects the model solution.

14) Employ open-source software tools to improve the efficiency of the modeling process. There are a number of freely available software tools that can be used to make the modeling process more efficient and less prone to error. The following is a list of some of them:

- Employ version-control software to help keep track of the versions of the evolving model software that is used in a project.
- There are community software packages for model verification that have been developed and thoroughly tested. An example is the Model Evaluation Tool (MET) that was designed for the WRF but can be applied to output from any model. The MET will calculate standard or feature-based verification metrics.
- Graphical user interfaces are convenient ways of interfacing with modeling software, to configure and run the model. It simplifies the configuration of the domains, the running and monitoring of

the model, and the visualization of the output. An example is the WRF portal.
- Many open-source software packages are available for analysis and visualization of observations and model output, including the R statistics language and the NCAR command language.

The above mentioned model configuration and optimization process, even when based on compromises, can possibly involve running and carefully verifying more than 50 model runs. The model will sometimes need to be evaluated for a significant number of events or study periods. Ideally, each combination of parameterizations and lateral boundary configurations should be tested for each simulation period. To save time, it may be safe to first perform the tests of different parameterization combinations and then use the best one or two configurations in the lateral boundary sensitivity tests. Regardless of whether shortcuts can be justified, this overall process will require considerable computational and human resources, which should be budgeted, from the start, into the design of a modeling effort.

CONCLUSIONS. This paper provides a discussion of best practices associated with the use of atmospheric models. The suggestions emphasize fairly elementary applications of models and do not encompass the use of the relatively more complex ensemble modeling systems or more advanced data-assimilation approaches. The hope is that it will encourage model users to become more aware, either through self study or through enrollment in a formal course in NWP, of practices that will enable them to use these complex numerical tools more effectively. A corollary is that "on-the-job training" is generally not sufficient to teach undergraduate or graduate students how to properly use models.

An interesting point is that a scientist could, at an intellectual level, agree with the suggestions recommended here and be ready to adopt many of them. However, for this scientist to obtain funding for model-based research, funding agencies need to be prepared to support the sometimes time-consuming process described here. Proposal reviewers need to agree with the process as well. Thus, there perhaps may be institutionalized disincentives for adopting better modeling practices. Further, regarding the human and computational resources required to adopt the best practices described, it is arguable that the efficiencies gained by following some of the recommendations will at least partially offset the additional work involved with adopting others.

ACKNOWLEDGMENTS. This manuscript benefited greatly from suggestions provided by Richard Anthes, Chris Davis, Jimy Dudhia, Joshua Hacker, Jason Knievel, Yubao Liu, Dorita Rostkier-Edelstein, Robert Sharman, David Stauffer, David Stensrud, and Wei Wang. Matthew Parker, Gary Lackmann, and an anonymous reviewer provided many additional valuable suggestions. Graphic art is by Cindy Halley Gotway.

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CUSTOMIZED SPATIAL CLIMATE MODELS FOR NORTH AMERICA

by Daniel W. McKenney, Michael F. Hutchinson, Pia Papadopol, Kevin Lawrence, John Pedlar, Kathy Campbell, Ewa Milewska, Ron F. Hopkinson, David Price, and Tim Owen

Natural Resources Canada, Canadian Forest Service, and their partners have developed spatial spline models and gridded datasets for North America for a wide variety of variables, time steps, and spatial resolutions.

Climate is a fundamental driver of life. Plant and animal distribution, abundance, and productivity are all closely tied to environmental regimes driven by temperature, precipitation, and solar radiation patterns. Critical biological processes, such as plant bud burst, flowering, and migration, both of animal populations and vegetation communities, are also linked to climate and weather conditions. Furthermore, human activities in many sectors, including food production, building construction, recreation, and power generation (solar, wind, hydroelectric), are closely connected to climate.

Not surprisingly, given the pervasive influence of climate, there is a high demand for reliable spatial climate data [indeed, this was very much the theme at the recent World Climate Conference 3: Better climate information for a better future (see www.wmo.int/wcc3/page_en.php); Munang et al. 2010]. In forestry and many other sectors, there is often a need for estimates well away from meteorological stations, which tend to be clustered near agricultural and urban areas. This need is met by "spatial" climate models, which can provide ▶

The Haliburton forest region in Ontario, Canada, with cumulus cloud formations. Photo by Mark Primavera, Natural Resources Canada.

estimates of climate at both specific locations of interest and in the form of regular grids. Projected climate change is another motivating factor in the development of these products. Spatial models of projected future climate allow these changes to be mapped, regional impacts to be assessed, and adaptation measures to be developed.

In response to the need for spatial climate data, researchers at Natural Resources Canada's Canadian Forest Service (CFS), the Australian National University (ANU), Environment Canada (EC), and the National Oceanic and Atmospheric Administration (NOAA) have collaborated to develop a wide range of spatial climate models. These models cover both Canada and the continental United States for a wide variety of climate variables, at time steps from monthly to daily, and across a range of spatial resolutions. The initial motivation in developing the models was to address forestry-related issues; however, many agencies and researchers have since used them in a variety of applications. Here we discuss the general method used to generate the models, with particular attention paid to the assessment of their predictive accuracy (as opposed to model fit), and describe the array of products available and how they may be accessed. We also briefly describe some of the wider applications of these models and outline expected further developments. Our overall intent is to contribute to the wider awareness of these products.

CLIMATE DATA. All spatial climate modeling begins with, and ultimately depends on, data from meteorological stations. In Canada, these data mostly originate from Environment Canada, although there are other station networks available in some regions (e.g., summer fire weather stations). In the United States, NOAA's National Climatic Data Center (NCDC) is the largest provider of climate data. Both of these agencies provide a wide variety of data products that have been error checked to varying degrees. Indeed, data quality is often taken for granted but considerable effort is expended in both Canada and the United States to provide consistent, long-term, reference-quality climate data and weather records (e.g., see Hutchinson et al. 2009; Hopkinson et al. 2011; Karl and Williams 1987; Vose et al. 2003; Peterson and Owen 2005; Menne et al. 2009, 2010). Despite extensive quality control measures, however, there can often be errors or inconsistencies that make it past the checks as well as inaccuracies inherent to the instrumentation used to measure the various climate metrics recorded at each station (i.e., measurement errors). For these reasons, among others, it must be remembered that spatial climate models are at best an approximation of actual climate. Both modelers and users should be acutely aware of data quality issues (e.g., Daly 2006; Hopkinson et al. 2011).

Another important data issue, particularly for disciplines such as forestry, which require historical climate records, is the variation in the number of climate stations through time and space. Prior to about 1930, there were very few weather stations in Canada, and far northern regions continue to be underserviced in the modern era [see McKenney et al. (2006a) for maps illustrating the varying number of stations over time]. The situation has been much better for the United States, though some data gaps exist (Guttman and Quayle 1996; Kunkel et al. 2005). Data deficiencies should be kept in mind, especially when using climate models covering older periods and/or northern regions. Error diagnostics and assessments of predictive error are discussed below. These are essential for detecting and correcting data errors and model deficiencies, and for providing users with reliable measures of predictive accuracy of the fitted climate models.

GENERATING CLIMATE MODELS AND MAPS. All the climate models reported here have been generated using thin-plate smoothing splines, as implemented in the ANUSPLIN climate modeling software (e.g., Hutchinson 2011). The earliest applications of thin-plate smoothing splines were described by Wahba and Wendelberger (1980) and Hutchinson and Bischof (1983), but the methodology has been further developed into an operational climate mapping

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-10-3132.1

In final form 14 June 2011

tool at the ANU over the last 20 years. ANUSPLIN has become one of the leading technologies in the development of climate models and maps, and has been applied in North America and many regions around the world (e.g., New et al. 2002; Hijmans et al. 2005; Rehfeldt 2006; Hutchinson et al. 2009). As documented in Daly (2006), ANUSPLIN belongs to the class of climate interpolation methods that can account for spatially varying dependences on elevation, a dominant predictor that is closely aligned with many controlling physical factors. A key strength of the ANUSPLIN method, in contrast to local regression methods, is its dependence on *all* the data (i.e., every data point observed for a single time slice contributes to the model fitted to minimize the generalized cross validation). This permits the robust and stable determination of dependencies on the predictor variables, particularly in data sparse, high-elevation regions.

ANUSPLIN is essentially a multidimensional "nonparametric" surface fitting method that has been found particularly well suited to the interpolation of various climate parameters, including daily maximum and minimum temperature, precipitation, and solar radiation. The underlying mathematics have been described in Wahba (1990) and Hutchinson (2011) (and references therein), so here we describe only the basic elements. The formal relationship between smoothing spline and kriging methods is well known (Matheron 1981; Dubrule 1983) and has been examined in a more practical setting by Hutchinson and Gessler (1994). A general representation for a thin-plate smoothing spline model fitted to n data values z_i at positions x_i is given by Hutchinson (1995) as

$$z_i = \hat{f}(x_i) + \varepsilon_i \ (i = 1, \ldots, n),$$

where f is an unknown function to be estimated, subject to a general smoothness condition and matching the n data values z_i to within an appropriate degree of error, as represented by the ε_i. The ε_i are considered to be random errors (with zero mean) that account for measurement error as well as deficiencies in the spline model, such as local effects below the resolution of the data network.

Contrary to common perception, a multivariate thin-plate smoothing spline is neither a piecewise second- or third-order polynomial nor a tensor product of such. It is in fact a true multivariate generalization of the univariate cubic smoothing spline. This depends on sophisticated numerical methods, as described in Wahba (1990) and implemented in the ANUSPLIN software, to achieve a computationally efficient solution. A second misconception is that the climate fields interpolated by ANUSPLIN are always smooth and hence incapable of matching strong gradients in the data. In practice, strong horizontal gradients are often associated with strong gradients in elevation, so a smooth dependence on elevation can effectively represent such strong climatic gradients. However, where there are minimal observations (i.e., station data), smoothing splines can have difficulty matching strong gradients in the dependency of the climate surface on elevation, as manifested in temperature inversions and across sharp rain shadows.

The parameters for the basic model, along with the amount of data smoothing, are usually estimated by minimizing a diagnostic called the generalized cross validation (GCV). This is normally a reliable measure of the predictive error of the fitted smoothing spline function that is discussed further below. It is calculated by implicitly removing each data point in turn and summing, with appropriate weighting, the square of the difference of each omitted data value from the spline fitted to all other data points. When fitting precipitation fields, it is currently recommended to apply a square root transformation to the precipitation in the surface fitting procedure to reduce skewness in the precipitation data (Hutchinson 1998; Hutchinson et al. 2009). This equilibrates the observed variability in precipitation between small and large values. The effectiveness of this transformation has been confirmed by its ability to allow the detection of subtle observation errors, such as missing precipitation values recorded as zero in low-rainfall areas, a relatively common data error. ANUSPLIN automatically corrects for the small negative bias that results from this transformation (Hutchinson 2011).

In most standard applications, the x_i represents longitude, latitude, and appropriately scaled elevation. Hutchinson (1995) has shown that it is appropriate to multiply elevation by a factor of 100 in relation to horizontal position when using trivariate splines to model precipitation. This agrees with the accepted relative horizontal and vertical distance scales of atmospheric dynamics (Daley 1991) and underlines the dominant impact of elevation in these spatial models. Sharples et al. (2005) have demonstrated that the optimal spatial resolution of this elevation dependence is around 5–10 km, in line with previous studies. While the trivariate model is robust and well aligned with the controlling physical processes, the model, as indicated above, is still subject to the limitations imposed by sparse data networks. Thus, for example, the spline model has been found to be deficient in representing precipitation gradients across the remote highlands of Bolivia and northern Peru, where very few long-term climate stations have been established (Killeen et al. 2007). Furthermore, comparison with satellite temperature data in western Canada suggested limitations to the spline approach in relation to certain land cover types, very high elevations, and large water bodies, where climate stations were few and unrepresentative; outside these data sparse areas, the models estimated well (Bussières and Milewska 2010).

Coastal temperature gradients, temperature inversions caused by cold-air pooling, and slope and aspect effects on precipitation (e.g., rain shadows) are well known in parts of North America, especially in coastal and mountainous areas (cf. Daly et al. 2008). Previous work has been done to represent these effects in ANUSPLIN models by incorporating additional predictors, such as distance from large water bodies and terrain variables such as slope and aspect (Hutchinson 1995). However, these effects are not simulated explicitly in our North American climate models. The incorporation of additional local predictors has been a particular challenge in Canada, where the number of data points representing these areas is very small. This is especially true in northern Canada, which contains just 5% of the available Canadian station network (Hutchinson et al. 2009). However, it should be noted that additional predictors, even when robustly calibrated, do not always improve the predictive accuracy of statistical models. Thus, Jarvis and Stuart (2001) found that more sophisticated interpolators, such as kriging and splines, required fewer additional predictors than less sophisticated methods to interpolate daily temperature, with a partial spline dependence on elevation yielding the best results.

ANUSPLIN can be configured in various ways. For example, the software can incorporate linear submodels to form a partial spline (Hutchinson 1991; Jarvis and Stuart 2001). Such analyses have been used to incorporate physical, process-based topographic influences for interpolating monthly evapotranspiration and pan evaporation data (McVicar et al. 2007). ANUSPLIN can also support exact interpolation through the climate station data values. Exact interpolation essentially assumes no error in the station data and can result in steep, questionable gradients between stations. Nevertheless, in situations where data are limited, and the statistical relationship between the climate variable of interest and the predictor variables is poorly supported, the capability to modify the structural form and nature of the final fitted function has proven to be useful.

Importantly for practical applications, the spline models can be easily resolved to any location (e.g., forest research plots, plantation sites, vegetation survey locations, farms) by providing site values for each independent variable—typically latitude, longitude, and elevation. This is perhaps a somewhat subtle point—with longitude and latitude as the independent variables, the models are *spatially continuous*. Elevation values, if not known, can be estimated via readily available digital elevation models (DEMs). Maps are generated by supplying a regular grid of the independent variables—usually in the form of a DEM. Most of our standard Internet map products make use of a 300-arc-second-resolution (approximately 10 km) DEM that was developed from Canada's 1:250,000 National Topographic Series topographic data (see Lawrence et al. 2008 for details) and the Global 30 Arc-Second Elevation Data Set (GTOPO30) DEM available from the U.S. Geological Survey (USGS; see http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info). Higher-resolution maps have also been generated for mountainous areas and other locations where analysts have particular needs—catchment hydrology studies being one relevant example. Given the increase in computing power and data storage capacities, higher-resolution grids are now much more feasible, although for some variables (e.g., precipitation) there is a limit to how much extra information finer topographic (DEM) resolutions can provide (Sharples et al. 2005). Many of our web-accessible maps (described below) are variably resolved at scales appropriate for user-defined domains.

CLIMATE CHANGE MODELS. We have also generated a suite of climate change products [see McKenney et al. (2006b) for full details; Joyce et al. 2011; Price et al. 2011] using data made available following the Intergovernmental Panel on Climate Change's (IPCC) Third and Fourth Assessment Reports (Houghton et al. 2001; Alley et al. 2007). The monthly time series of surface estimates for certain desirable variables, as projected by four general circulation models (GCMs) for different forcing scenarios of future greenhouse gas emissions [as described in Nakicenovic and Swart (2000)], were downloaded from publicly accessible Internet sites. These climate change projections are necessarily very coarse in nature, with grid spacings of 150 km or greater, and hence generally require "downscaling" to a more relevant resolution to be useful for impacts studies. In our case, the raw GCM outputs were interpolated after converting them to anomalies relative to the

1961–90 period (as simulated by the same GCM). These anomaly surfaces have also been integrated at the locations of more than 7,000 climate stations in the United States and Canada, and the predicted changes at these locations added to the 1961–90 station normals. This has provided a network of stations with projected climate values that incorporated both established site-to-site variation in climate as well as the broad-scale average changes predicted by the GCMs. Besides interpolating these models of future climate for each month of each year through to 2100 (Price et al. 2004), we have also generated average changes for three future periods (2011–40, 2041–70, and 2071–2100) (McKenney et al. 2006b; see also Joyce et al. 2011; Price et al. 2011).

CLIMATE PRODUCTS. Table 1 provides an overview of the "primary" climate surfaces currently completed. Many of the variables listed in Table 1 have been modeled at a number of different scales and time steps. Daily minimum and maximum temperature and precipitation are primary

Table 1. Climate variables for which models have been generated.

Parameter	Units	Time step[a]	Type[b]	Period covered	Area covered[c]
Minimum and maximum temperature	°C	m	n	1931–60, 1961–90, 1971–2000	CA, NA
			h	1901–2008	CA, NA
		w	n	1961–90, 1971–2000	CA
			h	1961–2003	CA
		d	h	1950–2008	CA
Precipitation	mm	m	n	1931–60, 1961–90, 1971–2000	CA, NA
			h	1901–2008	CA, NA
		w	n	1961–90, 1971–2000	CA
			h	1961–2003	CA
		d	h	1950–2008	CA
Solar radiation	MJ m^{-2}	m	n	1961–1990	CA, NA
Photovoltaic potential	MJ m^{-2}	m	n,h	1971–1994	CA
Sunshine	h	m	n	1961–1990; 1971–2000	CA
Potential evapotranspiration	mm	m	n	1961–1990, 1971–2000	CA, NA
Climate moisture index[d]	cm	m	n	1961–1990, 1971–2000	CA, NA
Relative humidity	%	m	n	1961–1990	CA, NA
Vapor pressure	kPa	m	n	1961–1990	CA
Evaporation (pan and lake)	mm	m,w	n,h	1961–1990	CA
Extreme minimum and maximum temperature	°C	a,m	n	1961–1990, 1971–2000	NA
		a,m	h	1961–2000	NA
Frost-free days	d	a	n	1961–1990	CA
Avg wind speed	km h^{-1}	m	n	1961–1990	CA, NA
Maximum wind gust	km h^{-1}	m	n	1961–1990, 1971–2000	CA
Rainfall	mm	m	n	1931–60, 1961–90, 1971–2000	CA
Snow depth	cm	m	n	1961–90, 1971–2000	CA
			h	1955–2008	

[a] The time unit of the climate model: a = annual, m = monthly, w = weekly, and d = daily.

[b] The type of climate model: n = normal (i.e., long-term average) and h = historical (i.e., models generated for each year over a given period).

[c] CA = Canada; NA = Canada and the United States.

[d] As defined by Hogg (1997).

variables that are used in many applications and, as such, considerable effort has gone into summarizing them in various ways. For example, daily minimum and maximum temperature surfaces are available in the form of i) monthly averages for a variety of 30-yr "normal" periods (e.g., 1901–30, 1931–60, 1961–90), ii) monthly averages for each year over the period 1901–2008, and iii) daily values for each day over the period 1950–2007. Similar products are available for precipitation. The remainder of the

Table 2. Bioclimatic variables generated from Canadian and North American temperature and precipitation surfaces at the monthly-mean and historical monthly time steps.

Variable	Description
Annual mean temperature	Avg of mean monthly temperatures
Mean diurnal range	Avg of monthly temperature ranges
Isothermality	Variable 2 ÷ variable 7
Temperature seasonality	Standard deviation of monthly-mean temperature estimates expressed as a percent of their mean
Max temperature of warmest month	Highest monthly maximum temperature
Min temperature of coldest month	Lowest monthly minimum temperature
Temperature annual range	Variable 5 – variable 6
Mean temperature of wettest quarter	Avg temperature during 3 wettest months
Mean temperature of driest quarter	Avg temperature during 3 driest months
Mean temperature of warmest quarter	Avg temperature during 3 warmest months
Mean temperature of coldest quarter	Avg temperature during 3 coldest months
Annual precipitation	Sum of monthly precipitation values
Precipitation of wettest month	Precipitation of the wettest month
Precipitation of driest month	Precipitation of the driest month
Precipitation seasonality	Standard deviation of the monthly precipitation estimates expressed as a percent of their mean
Precipitation of wettest quarter	Total precipitation of 3 wettest months
Precipitation of driest quarter	Total precipitation of 3 driest months
Precipitation of warmest quarter	Total precipitation of 3 warmest months
Precipitation of coldest quarter	Total precipitation of 3 coldest months
Growing season start	Julian day number at start of growing season
Growing season end	Julian day number at end of growing season
Growing season length	Length of growing season (days)
Total precipitation period 1	Total precipitation 3 weeks prior to growing season
Total precipitation period 2	Total precipitation during first 6 weeks of growing season
Total precipitation period 3	Total precipitation during the growing season
Total precipitation period 4	Variable 25 – variable 24
Growing degree days period 1	Degree days (above 5°C) for 3 weeks prior to growing season
Growing degree days period 2	Degree days (above 5°C) for first 6 weeks of growing season
Growing degree days period 3	Degree days (above 5°C) for growing season
Growing degree days period 4	Variable 29 – variable 28
Annual minimum temperature	Overall average of monthly average minimum temperatures
Annual maximum temperature	Overall average of monthly average maximum temperatures
Mean temperature period 3	Average temperature during growing season
Temperature range period 3	Highest maximum temperature minus lowest minimum temperature during growing season

variables in Table 1 have been developed for specific applications and generally cover shorter periods and fewer time steps.

The temperature and precipitation variables can also be used to calculate a suite of "bioclimatic" variables (Table 2). These variables summarize temperature and precipitation in ways that are potentially important to plants and animals and are arguably more intuitive for some purposes. They include classic temperature-based bioclimatic indices, such as growing season length, growing degree-day sums, minimum temperature of the coldest month, and annual mean temperature, which are often used as input to process-based models of ecosystem dynamics (e.g., Sitch et al. 2003) as well as numerous agricultural crop models. These variables are available for both 30-yr normal periods and historical monthly time steps. For our climate change work, we generated spatial models of future climate based on a variety of GCMs and emissions scenarios (Table 3), including three future normal periods for the bioclimatic summary variables listed in Table 2 as well as temperature and precipitation, as previously noted.

More than 60,000 of our climate models can be viewed in map format online (http://cfs.nrcan.gc.ca/projects/3?lang=en_CA). This number does not include the historical daily climate models because their file size prohibits rapid interactive mapping (i.e., there are more than 50,000 daily models alone). The Web mapper makes use of MapServer, an open-source project to support spatial mapping on the Internet (see http://mapserver.org). These data are managed in an Oracle Database framework that supports large dataset management applications (www.oracle.com/index.html). Though the Web mapping system is not a geographic information system (GIS) per se, it does have some GIS functionality, such as data layer selection, zoom capabilities, and a simple query tool. A recent feature is the option to download model estimates for user-supplied locations. The volume of customized data requests has grown significantly over time, and this new capacity should facilitate the use of these climate models while easing the burden of responding to data requests. It is currently not possible to download gridded data directly from the website. However, for those using the OpenGIS data protocols, maps can be drawn in GIS using the Web Map Service protocol. For the time being, gridded data requests can be made by contacting the corresponding author.

HOW GOOD ARE THE MODELS? Our climate models are assessed for predictive accuracy and bias using a variety of metrics. Several measures of model quality are also provided as standard output with each ANUSPLIN run. The signal, given by the trace of the influence matrix (Wahba 1990), indicates the complexity of the surface and varies between a small positive integer and the number of weather stations used in each model. Hutchinson and Gessler (1994) suggest that the signal should be no more than about half the number of data points. Models with such signals tend to be more robust and reliable in data-sparse regions. This is particularly important for applications in forested regions, where weather station coverage is often sparse. The GCV described above is also normally a reliable measure of the predictive capacity of the models. Its main weakness is that it can lead to undersmoothing of noisy data when there is significant short-range correlation in the data (Hutchinson and Gessler 1994). It can also be biased when the data network has uneven density. The analysis by Hutchinson (1998) indicates that in the

TABLE 3. GCMs, versions, and emissions scenarios for which surfaces of North American future climate have been generated.

GCM	Version*	Scenario	Period**
Canadian Centre for Climate Modelling and Analysis Coupled GCM (CGCM)	2.0 3.1	A2, B2 A2, A1B, B1	1900–2100 1961–2100
Commonwealth Scientific and Industrial Research Organisation (CSIRO)	2.0 3.5	A2, B2 A2, A1B, B1	1961–2100 1961–2100
National Center for Atmospheric Research (NCAR)	PCM CCSM3.0	A2, B2 A2, A1B, B1	1961–2099 1961–2099
Hadley Centre Coupled Model (HadCM)	3.0	A2, B2	1950–2099
Center for Climate System Research Model for Interdisciplinary Research on Climate (MIROC)	3.2	A2, A1B, B1	1961–2100

* PCM = Parallel Climate model; CCSM3 = Community Climate System Model, version 3.

** Raw GCM data were obtained for the period listed; future projections are for three future normal periods (2011–40, 2041–70, 2071–2100) and various other time steps of interest.

precipitation context, short-range correlation operates over distances less than 10 km. Thus, short-range correlation has limited impact on relatively sparse datasets. Bias due to uneven network density can be assessed by calculating predictive errors at spatially representative locations withheld from the fitting procedure. McKenney et al. (2006a) and Hutchinson et al. (2009) have verified the accuracy of GCV in Canada-wide analyses using explicitly withheld data that equisampled the longitude, latitude, and vertically exaggerated elevation space covered by the data networks. The GCVs were closer to the withheld error statistics for temperature, which is more reliably estimated from limited data networks than is precipitation. McKenney et al. (2008) also demonstrated good agreement between GCVs and spatially representative withheld error statistics for spatial analyses of solar radiation. The two error statistics also agreed in their relative assessments of predictive accuracy of three different spline model formulations, confirming the ability of GCV to discriminate between different models without the need for explicitly withholding test data.

Hutchinson et al. (2009) provided a comprehensive withheld data assessment of their fitted daily temperature and precipitation models, by calculating the mean error (i.e., bias) and mean absolute error (i.e., accuracy) of the differences between the estimated values and the recorded withheld values at specific spatially representative locations. This analysis showed that the predictive errors generated for daily thin-plate smoothing spline interpolations compared well with those reported for other methods and locations using denser data networks. Errors in estimating daily rainfall occurrence of around 17% compared well with the one other study for North America where this statistic was reported. Daily rainfall occurrence is a critical issue in, for example, modeling crop disease (e.g., Kang et al. 2010). A recent revision of this analysis using data corrected for time of observation further reduced these predictive errors by about 15% and 22% for the summary temperature and precipitation residuals, respectively (Hopkinson et al. 2011), further underlining the importance of data quality issues.

Table 4 summarizes average withheld error estimates for our temperature and precipitation models across spatially representative locations at the monthly normal, historical monthly, and historical daily time steps. Errors associated with the normal surfaces are quite small, reflecting the greater spatial coherence of monthly normals. The corresponding values in Table 4 are similar to those reported by Price et al. (2000) and Daly et al. (2008). They are

Table 4. Mean absolute (i.e., accuracy) and mean (i.e., bias) withheld errors associated with spatial models of temperature and precipitation. Fifty spatially representative withheld stations were used to test the daily [see Hutchinson et al. (2009) for details] and monthly normal (Hopkinson et al. 2011, manuscript submitted to *J. Appl. Meteor. Climatol.*) models that cover Canada; 200 spatially representative withheld stations were used to test the monthly historical models that cover Canada and the United States (see McKenney et al. 2006a for details).

Parameter	Units	Time step[a]	Model type[b]	Period	Mean absolute error	Mean error
Minimum temperature	°C	m	n	1971–2000	0.6	0.04
		m	h	1950–2000	1.3	0.02
		d	h	1961–1990	1.6	−0.02
Maximum temperature	°C	m	n	1971–2000	0.4	0.23
		m	h	1950–2000	0.9	0.05
		d	h	1961–1990	1.1	0.07
Precipitation	%	m	n	1971–2000	6.7	−2.30
		m	h	1950–2000	30.3	2.50
		d	h	1961–1990	8.9[c]	−1.60[c]

[a] The time unit of the climate model: m = monthly and d = daily.

[b] The type of climate model: n = normal (i.e., 30-yr average) and h = historical (i.e., models generated for each time step over a given period).

[c] Errors associated with daily precipitation models are from annual totals of daily values averaged over withheld stations for the stated period (following Thornton et al. 1997).

not much larger than the measurement error that can be attributed to the recording instruments. The historical monthly errors are larger, reflecting the challenges of modeling shorter time steps, with monthly temperature errors approximately twice the monthly normal temperature errors. The daily models have slightly larger errors for temperature. However, assessing errors associated with daily precipitation models is problematic (Thornton et al. 1997); thus, we follow the convention of summing daily values to annual totals. Models with shorter time steps are generally expected to have larger errors because they are attempting to capture phenomena that are much more variable in space and time. For example, convective rainfall events often occur over a limited area and can be easily missed by station networks. Thus, while daily models may describe daily temperature extremes reasonably well, they have limited accuracy in describing daily precipitation extremes (Hutchinson et al. 2009). For many applications, the key information required for daily precipitation extremes consists of statistics describing overall likelihood, which are more accurately described by interpolating the key parameters describing these statistics rather than inferring the statistics from individually interpolated daily values. Models using other approaches and additional predictors, such as radar rainfall data (e.g., Haberlandt 2007; Overeem et al. 2009), climate model outputs, and detailed topographic analyses (Böhner 2005), have the potential to further improve accuracy; although, as noted above, additional predictors do not always improve overall predictive accuracy.

USAGE AND APPLICATION. These climate products have been applied in a number of forest-related areas, such as assessing plant hardiness (McKenney et al. 2007a), climate change impacts on forest resources (McKenney et al. 2007b; Price and Scott 2006), nonindigenous species modeling (Venier et al. 1998; Yemshanov et al. 2009), forest productivity modeling (McKenney and Pedlar 2003; Yemshanov et al. 2007), and seed movement (McKenney et al. 2009). A variety of users from academic institutions and government agencies have applied the data to a range of other topics, including wildlife research (Chu et al. 2008), human health and welfare (McLeman et al. 2010), crop yields (Pearson et al. 2008; Cabas et al. 2010), and photovoltaic energy production (McKenney et al. 2008).

CONCLUSIONS AND FUTURE DIRECTIONS. Spatial climate modeling is an ongoing task, as source datasets change in coverage and quality (e.g., Canadian station numbers have been declining in recent years) and as new applications and methods evolve. In addition to continuously updating and improving existing models, there are many climate variables and time steps for which models could be generated. Here we outline several projects that will be a focus in the near future.

Historical daily climate models provide estimates of past daily temperature and precipitation over a selected period. Such data are particularly valuable as input for models that simulate processes such as plant growth, fire severity, and plant phenology. We currently have daily models that cover the period 1950–2007 for Canada only (Hutchinson et al. 2009). In collaboration with Environment Canada and NOAA's NCDC in the United States, we are in the process of generating North American–wide daily models for this same period and possibly for earlier decades where the data allow. These models will employ datasets that correct for issues such as disparities in "climate day" definitions and recording times between the U.S. and Canadian networks.

Visitors to our website (http://cfs.nrcan.gc.ca/subsite/glfc-climate) are currently able to view maps and download climate values for a set of user-supplied locations. In the future, we hope to launch a function that will allow users to download customized gridded data as well. For simple requests, this will eliminate the need for users to contact us directly. For more complex requests (e.g., involving spatial resolutions not available from the website), users will still need to contact the corresponding author. Another planned enhancement to the website involves the addition of detailed daily summaries. This function would allow users to obtain graphical and tabular summaries of historical temperature and precipitation values for any given location.

There can be a significant lag between when the time measurements are recorded at meteorological stations and when quality-controlled data are made available to the public. We plan to continue to update our models as new station data are made available. For example, when the 2010 records are available, we will generate new normals for the 1981–2010 period. The fifth IPCC report is due out in 2014 and will likely entail improved and updated climate change products, though certain GCMs and scenarios may be added to our current suite of models prior to that. Finally, the ANUSPLIN package continues to be upgraded. For example, "additive" spline models have been developed that can robustly incorporate spatially varying dependencies on several additional independent variables without violating the "curse of dimension" (Sharples and Hutchinson 2004).

In conclusion, there is a growing demand for spatially reliable climate models at a variety of temporal and spatial resolutions. This paper has provided details about our climate models—how they are developed and evaluated, how they can be accessed, and how they will be updated and improved in the near future. Models are most valuable when they are used. We hope this paper raises awareness of our climate models and encourages potential users to visit the website or contact us for further information.

ACKNOWLEDGMENTS. We thank several staff members of Environment Canada and Natural Resources Canada who have supported and encouraged our work over time, including Bill Hogg, Anna Deptuch-Stapf, Robert Morris, Robert Vet, Lucie Vincent, Val Swain, and Bob Stewart. We also thank Marty Siltanen of the Canadian Forest Service for his assistance in generating various climate change products. We also thank the reviewers for their comments and assistance in improving the manuscript.

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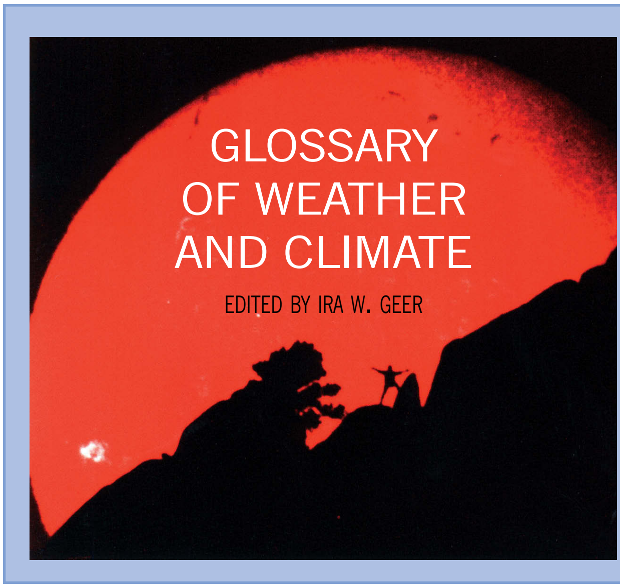

RESURGENCE IN ICE NUCLEI MEASUREMENT RESEARCH

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Measuring systems for atmospheric ice nuclei are undergoing development anew and are beginning to meet the needs for studies of aerosol effects on ice-containing clouds.

Understanding and predicting the formation of ice in clouds and its possible relation to the changing state of atmospheric composition (aerosols and gas phase) remain enigmatic. Such knowledge and capabilities are critical to quantifying the role of aerosols and their changing compositions on clouds, precipitation, and climate (Denman et al. 2007; Levin and Cotton 2009). This challenge is a major motivation for renewed attempts to measure ice nucleation processes in general, and to design and deploy new portable systems for measuring ice nuclei (IN), the particles that are considered the only means for initiation of the ice phase at temperatures warmer than about −36°C in the atmosphere. The fundamental desire to understand ice nucleation remains the same as when such research began in earnest more than 60 yr ago. The search to identify atmospheric ice nuclei lapsed during the 1970s–80s

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-10-3119.1

In final form 1 August 2011

and did not fully recover until the start of this century. During the same period, the general field of ice nucleation, especially ice nucleation within biological systems, developed considerably. Indirect studies of ice formation in clouds via remote sensing and in situ measurements also progressed. The reasons for a pause in research about ice nuclei and ice formation in clouds included the recognition (through workshops) of shortcomings in ice nucleation measurements, the unrealized promise of efforts to control clouds and precipitation through the application of artificial ice nuclei, and the increased emphasis on numerical modeling studies of clouds. Most importantly, discrepancies became clear between number concentrations of ice nuclei and ice crystal concentrations in clouds. This left an impression that either ice nuclei measurements were too inaccurate or basically irrelevant in explaining the evolution of ice in clouds. It is now solidly established that secondary processes increase ice crystal concentrations in some clouds far beyond the initial stage dominated by ice nucleation, that cloud mixing processes can easily disguise the relation between ice nuclei and ice particle concentrations in clouds, and that there have been serious artifact issues present in the ice particle measurement records. We expound on these and other points herein. Our main focus is to report on the accuracy and precision of current ice nuclei instruments, and, in doing so, to note progress made toward addressing apparent shortfalls in past ice nuclei measurements.

THE MEASUREMENT CHALLENGE. It is important to recognize the role of ice nuclei in the context of how the distribution of the ice phase is realized in clouds. It is conceivable that ice nuclei may entirely explain the formation of ice in some clouds. Nevertheless, a more complex series of processes are often involved in determining the microphysical composition of clouds and formation of precipitation, including the secondary ice formation processes (ice crystals formed from pre-existing ice), the seeding of ice crystals from higher and colder clouds, and the redistribution of ice particles in and around clouds resulting from cloud and atmospheric dynamics (see Fig. 1). Describing the contribution of ice nucleation to the formation of single ice crystals and how this relates to the aerosol particles entering a cloud is the realm of ice nuclei measurements. That such measurements are extremely challenging was succinctly stated by Vali (1976) in his summary of the last formal international ice nucleation workshop:

> Historically, the measurement of ice nucleating activity has been found to be stubbornly difficult. Ice nucleation is sensitive to a large number of complex variables, so that the requirement that measurements reflect the reaction of the nuclei to the state of those variables in natural clouds is indeed a demanding one.

Ice formation may occur in clouds by both homogeneous and heterogeneous ice nucleation, so measurements must address temperatures extending from 0°C to the coldest tropospheric conditions. Clouds warmer than –36°C require ice nuclei. These particles may represent <1 in 10^6 of the aerosol population, presenting a difficult measurement challenge. Heterogeneous ice nucleation processes may include deposition nucleation on particles even in the absence of liquid cloud formation (below water saturation), ice formation either during the simultaneous action of ice nuclei as cloud droplet nuclei (condensation freezing) or during the subsequent lifting and cooling of cloud droplets (immersion freezing), and ice formation by the collision of cloud interstitial aerosols with cloud droplets [contact freezing; see Vali (1985)]. These conceptual processes, represented in Fig. 1, encapsulate additional dependencies of ice nucleation on temperature, humidity, and particle surface characteristics.

A valid question is, do ice nuclei measurements describe ice formation by aerosols entering clouds? To demonstrate relevance, these measurements must first quantify ice formation, that is, the number concentrations of ice crystals observed under specific conditions in clouds when other ice-generating processes are not occurring. Special circumstances and specific information are required to establish the existence of a 1:1 comparison between ice nuclei and ice crystal concentrations. A relatively simple cloud dynamical framework is needed in which updraft and cloud condensation nuclei (CCN) are well defined (because CCN and cloud dynamics determine the value of water vapor supersaturation achieved), conditions favoring secondary ice formation processes are avoided, and there is an instrument that can measure ice nucleation at the temperature and supersaturation conditions where ice is observed to form in the cloud. These requirements were met with some success in the recent Ice in Clouds Experiment (Eidhammer et al. 2010; Twohy et al. 2010; Pratt et al. 2010). Supporting such documentation, one wishes to know 1) that the various ice nuclei measurement methods being applied agree, or, if not, why they do not agree; and 2) that ice nuclei measurements

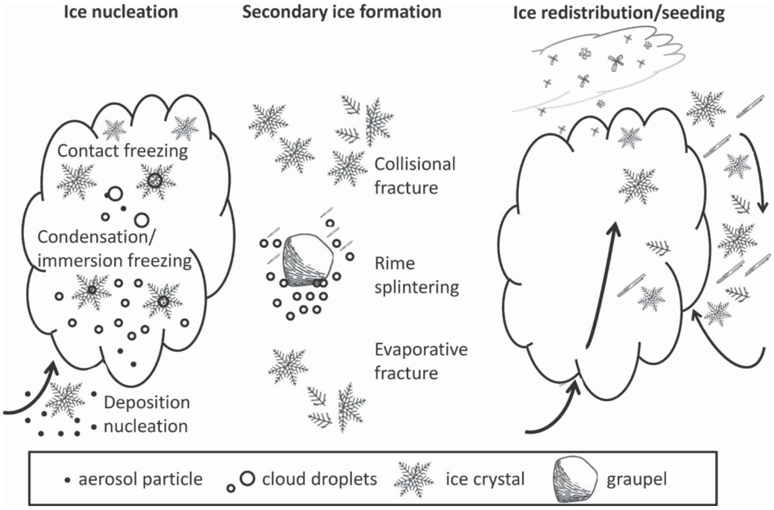

Fig. 1. Ice formation processes distinguishing ice nucleation occurring on aerosol particles from other processes affecting cloud particle composition, such as the formation of ice from secondary processes involving the collision of preexisting ice crystals (Vardiman et al. 1978), the splintering of ice off of graupel during the accretion of cloud droplets (Hallett and Mossop 1974), and the fracture of ice crystals exposed to dry air layers (Oraltay and Hallett 1989).

reproduce ice formation in the closest approximation to an atmospheric system that can be achieved in the laboratory, that is, with the simulation of cooling cloud parcels in a large expansion chamber. Here, we describe historical and more recent approaches to satisfying these other evidential needs.

A BRIEF HISTORY OF METHODS OF ICE NUCLEI MEASUREMENT AND THEIR VALIDATION. Ice nuclei measurement methods were first developed for atmospheric use in the 1940s. Some of the first measurements of ice nuclei in natural air used cloud chambers, creating clouds either by expansion cooling air (volumes from 10 L to many cubic meters) or by feeding warm, humid air into cold chambers of a similar size to create liquid clouds, and subsequently observing ice nucleation (e.g., aufm Kampe and Weickmann 1951; Mason 1962). The results showed extreme variability, the source of which could be not isolated readily because of the types of aerosols sampled, the methods used, or experimental artifacts. Some of the expansion chambers were portable for atmospheric measurements (e.g., Bigg 1957; Warner 1957). Continuous flow cloud or settling cloud chambers came later (e.g., Langer 1973) as the portable expressions of the diffusion cloud chamber concept, built in recognition of the need for near-real-time sampling from aircraft, and the possibility for long-term sampling at remote sites.

Beginning also in the 1960s, methods were developed for measuring the number concentrations of atmospheric IN collected onto filters or other substrate surfaces. This permitted "processing" of the collected particles, importantly, under independent control of temperature (T) and relative humidity (RH). In this method, the vapor pressure over the filter's surface is determined in a static manner by differential control of a warmer adjacent ice surface (the vapor source) and the colder substrate in a thermal gradient diffusion chamber (TGDC; see Fig. 2; Stevenson 1968), by passing air of separately controlled vapor pressure over the cold substrate surface at room pressure (e.g., Langer and Rodgers 1975), or by the instantaneous exchange of conditioned air over the cold substrate at low pressure in an isothermal static diffusion chamber

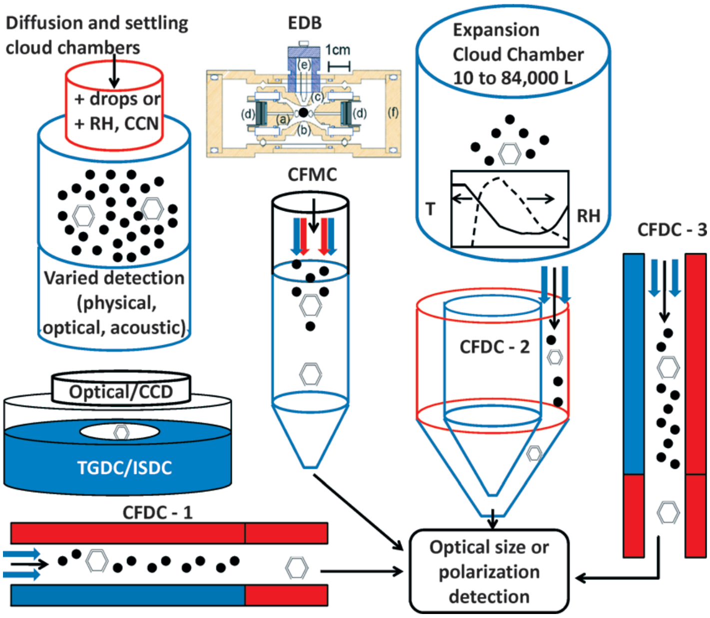

Fig. 2. Diagram showing the assortment of types of ice nucleus instruments described in the manuscript. Liquid droplet (black spheres) and ice crystal populations (hexagonal plates), aerosol sample flows (black arrows), and warm (red) and cold (blue) plates/ice surfaces are indicated (similarly, colored arrows indicate the warm and cold flow of dry or humidity-conditioned air).

(ISDC; see Fig. 2; Bundke et al. 2008). Issues leading to inaccurate measurements with this method are well documented (Vali 1976; Bigg 1990), including competition for water vapor by particles growing on the filter/substrate surface, control of the surface temperature, and interference with ice nuclei activity by heat transfer materials in between the filter and cold plate surface. Nevertheless, interest in this method remains strong because of the relative ease of collection and potential for large sample volumes.

During these early developments, investigators recognized the potential utility of comparing instruments in laboratory workshops. Consequently, a first international workshop on condensation and ice nuclei was held in Lannemezam, France, in 1967. A second international workshop on both condensation and ice nuclei was held in Fort Collins, Colorado, in 1970 (Grant 1971). The third workshop in Laramie, Wyoming, narrowed the focus to the measurement of IN (Vali 1975, 1976). These three workshops spanning a period of 8 yr recognized a variety of important issues for adequately measuring ice nuclei. For example, the dependence of ice nuclei activation on supersaturation was identified as a major factor in the divergent results among IN instruments noted in the second international ice nucleation workshop (Bigg 1971; Langer 1973), a finding that was reiterated in the third workshop (Vali 1975).

The development of continuous flow diffusion chamber (CFDC) devices was in direct response to the workshop findings and the need for portable instruments capable of obtaining continuous measurements for aircraft application. These instruments were designed to expose particles to steady temperature and RH conditions for up to about 10 s. The underlying design principle is to flow air containing particles (usually focused by sheathing it within dry airstreams) between warm and cold ice-coated surfaces to create exposure to an established temperature and vapor pressure field that is supersaturated with respect to ice and, if desired, water, at the position of the aerosol stream. The devices took two early forms regarding orientation and geometry: horizontal with parallel plates (Hussain and Saunders 1984; Tomlinson and Fukuta 1985; CFDC-1 in Fig. 2), and vertical with cylindrical walls (Rogers 1988; CFDC-2 in Fig. 2). Ice nucleation in CFDC instruments is detected by the differing properties of nucleated ice and liquid haze particles or water droplets, either by reducing the RH to ice saturation at the outlet region in order to evaporate only the liquid particles to create a strong size segregation of much larger ice crystals (Rogers 1988) or by taking advantage of the differences in scattering/polarization properties of ice and liquid particles (Nicolet et al. 2010). These instruments offer the advantage of varying *T* and RH, while removing substrate issues and allowing for unimpeded measurement even of high concentrations of IN through continuous exposure to an unlimited vapor source. The limitations of the CFDC method are the relatively small samples (~1–2 L min^{-1}) and the inability to assess contact-freezing nucleation because of the short measurement times.

During the 20 yr following the introduction of CFDC instruments, only the cylindrical version was utilized extensively and developed for sampling from either the ground or aircraft (Rogers et al. 2001). This instrument has continued to evolve with refrigeration control improvements, conversion from passive to active control of droplet evaporation, improved characterization of device performance, and improved interpretation of data through numerical modeling exercises and examination of sampling statistics (Petters et al. 2009; Richardson 2009; Eidhammer et al. 2010). More recently, new instruments have adopted the parallel plate design with horizontal (Kanji and Abbatt 2009) and vertical geometry (Stetzer et al. 2008; CFDC-3 type in Fig. 2). The CFDCs, as for any flowing system, also permit linking with devices to separate IN for physicochemical analyses using electron microscopy (e.g., Prenni et al. 2009a,b) or single-particle mass spectrometry (e.g., Cziczo et al. 2003).

Bundke et al. (2008) introduced a totally new ice nuclei instrument method, a continuous flow mixing chamber (CFMC) device that creates supersaturation by mixing an aerosol stream with warm, humid and cold, dry airstreams. This design permits higher sample volumes (up to 10 L min^{-1}), which are particularly useful for measurements at modestly supercooled temperatures. Detection is achieved by separating crystals with a virtual impactor and phase discrimination (circular depolarization). An autofluorescence detector for sensing biological components in IN has recently been linked to the instrument (Bundke et al. 2010).

Portable devices for studies of contact-freezing nuclei have been used in the past (Deshler and Vali 1992). The critical need in near–real time is a relatively rapid collection of particles to supercooled droplet surfaces in order to estimate the potential number concentrations per volume. Vali (1976) describes a drop-freezing device utilizing electrostatic precipitation, while Cooper (1980) interpreted the freezing following the settling of drops onto particles collected on filters as being indicative of contact-freezing nuclei concentrations. More recently, contact-freezing studies have been described (Svensson et al. 2009) that employ an electrodynamic balance (EDB) to microposition collecting droplets in space without contact with surfaces. This device is also suitable for studying freezing of previously immersed ice nuclei. Ladino et al. (2011) describe a new device for monitoring contact freezing of aerosols with monodisperse droplets over limited collection times.

It is apparent that some ice nucleation devices focus on simulating the consequences of specific ice nucleation mechanisms, while others collect data that may or may not be interpreted in terms of mechanistic contributions but are designed to measure the totality of processes at play within the limitations allowed by the measurement method. Which of these approaches will be more successful in producing the desired predictive capability for ice formation in clouds remains to be seen.

A BUMPY ROAD FOR ATMOSPHERIC ICE NUCLEATION RESEARCH. A lull in atmospheric ice nucleation research (Fig. 3) occurred in coincidence with, and probably as a direct consequence of, the early series of international workshops. Interestingly, ice nucleation by biological entities (principally bacteria) became a major interest with practical applications, such as frost damage to plants and the winter survival of insects (e.g., Lee et al. 1995). We speculate that multiple factors were involved in the plateau of ice nucleation studies. There was recognition that progress in the understanding of atmospheric ice nucleation would require avoidance of the pitfalls of earlier measurement methods as revealed by the workshops (which motivated a period of developing new methods), funding in weather modification research that relied heavily on understanding ice nucleation properties declined (Garstang et al. 2005), emphasis on numerical studies of growing clouds, and research refocused toward other atmospheric issues, such as greenhouse gases and climate change. In addition, there was growing concern about the apparent disconnect between measurements of IN concentrations and ice crystal concentrations, especially as measured by advanced electro-optical instrumentation that came online in the 1980s (Knollenberg 1976). While some studies considered sources of these discrepancies in real behavior of ice nuclei, such as the response to transient conditions leading to high supersaturations in clouds (Rangno and Hobbs 1991; Rogers et al. 1994), the ability of ice nuclei instrumentation to assess activation in clouds was legitimately questioned.

Subsequently, to accurately represent the liquid and ice phases in clouds in developing global climate models, ice crystal concentration measurements were considered to be more realistic inputs than predictions based on the results of ice nucleus measurements because ice crystal number concentrations in clouds can sometimes exceed ice nuclei number concentrations by at least two orders of magnitude (Levin and Cotton 2009). While a full consideration of the sources of such discrepancies is beyond the scope of this article, we will note that gross comparisons of ice nuclei and ice crystal number concentrations in clouds are difficult to make in a meaningful way because clouds evolve past the ice nucleation stage. The degree of divergence depends on cloud type—it is worst in deep clouds and convection. The discrepancies are least in certain orographic wave clouds, which do not have strong secondary ice formation and ice redistribution processes (cf. Fig. 1) and allow directly relating ice evolution to the properties of aerosol and ice nuclei entering clouds (e.g., Eidhammer et al. 2010). Furthermore, it is now recognized that many circumstances result in erroneous measurements of small ice crystals because ice crystals larger than a few hundred microns can shatter on pieces of cloud particle measuring instruments near their sampling apertures (Korolev and Isaac 2005; Field et al. 2006; McFarquhar et al. 2007; Jensen et al. 2009; Korolev et al. 2011). Artifact crystal production

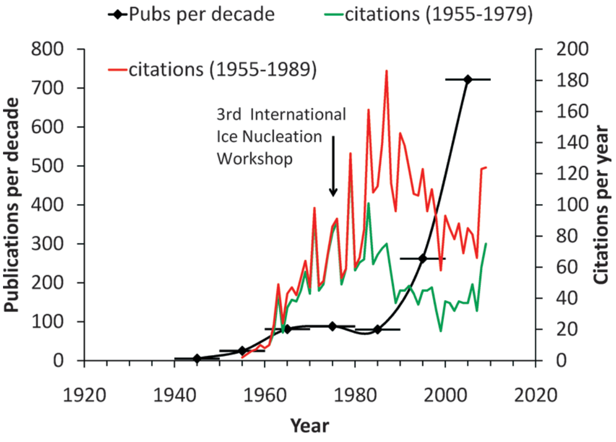

Fig. 3. Institute for Scientific Information (ISI) Web of Knowledge (Thomson Reuters) publications per decade and citations related to the terms "ice nuclei," "ice nucleation," "freezing nuclei," "sublimation nuclei," and "deposition nuclei" that are filtered for atmospheric-related studies from 1950–79 and 1950–89, demonstrating the 1970s–80s research lull and the interest in early publications that have recently begun to surge. Biological ice nucleation studies not directly relevant to the atmosphere have been excluded.

can be extreme in some circumstances, reaching an enhancement factor of 100. Although the full extent of artifact crystal generation is unknown, it is now clear that cloud ice crystal measurements need very careful consideration in evaluating the adequacy of ice nuclei measurements. New measurements are needed with new probe designs, because it may not be possible to remove small ice crystal artifact concentrations through software reanalyses alone (Korolev et al. 2011). It would seem to be productive for the ice crystal and ice nuclei measurement communities to consider their issues separately while joining to compare where artifact issues are minimized in clouds.

REVIVAL OF INSTRUMENT WORKSHOP AND MEASUREMENT CAMPAIGNS. A clear impetus for advancing ice nuclei measurement technologies comes from the need to understand the role of aerosols in climate change (Houghton et al. 2001; Denman et al. 2007). Numerical modeling systems are becoming capable of accepting detailed physical descriptions of ice nucleation and carrying studies to the scale of global impacts. Publications related to ice nucleation rose sharply in the last 10–15 yr, and a new generation of scientists is revisiting and citing studies done more than 20 yr ago (Fig. 3).

Despite sometimes divergent results, the results of early workshops indicated the importance of collaboration for shedding light on the performance of ice nuclei instruments by comparing how instruments respond to ice nucleating aerosols over a sufficiently wide range of thermodynamic conditions. The more recent development of controlled expansion chambers (Möhler et al. 2006) that permit simulations of cloud parcel formation and evolution adds a new tool for evaluating ice nuclei measuring capabilities.

In Europe, collaborative ice nucleation studies have been supported and coalesced through programs that promote group activities, for example, through programs such as Interdisciplinary Tropospheric Research: From the Laboratory to Global Change (INTROP), the former Atmospheric Composition and Climate European Network of Excellence (ACCENT) program, and the Integration of European Simulation Chambers for Investigating Atmospheric Processes (EUROCHAMP). Partly motivated and supported by these studies, the 2007 International Workshop on Comparing Ice Nucleation Measuring Systems (ICIS-2007), unofficially the Fourth International Workshop on Ice Nuclei, occurred in Germany in September 2007 (Möhler et al. 2008).

ICIS-2007 was formulated in the spirit of previous ice nucleation workshops. Nine different ice nuclei measuring systems were assembled at the Aerosol Interactions and Dynamics of the Atmosphere (AIDA) facility at the Karlsruhe Institute of Technology in Karlsruhe, Germany, to take advantage of the opportunity to compare cloud parcel simulations in the large (84 m^3) AIDA cloud chamber facility. An experimental comparison program was designed to focus measurements in the temperature range of AIDA expansions and to utilize particularly relevant natural ice nucleating aerosols or surrogates thereof. Participants made a conscious effort to avoid too formal a structure for collecting and comparing data. They saved formal intercomparison for future regular workshops and instead emphasized restarting the workshop concept and encouraging collaboration and learning, including the use of prototype instruments. The workshop compared and contrasted measurements made by a variety of devices used in the laboratory and field, with a secondary purpose of assessing measurement capabilities in terms of atmospheric relevance. Educational aspects were enhanced via lectures and discussions led, in some cases, by participants from the earlier workshops.

ENCOURAGING NEW RESULTS AND NEEDS FOR FUTURE STUDY AND DEVELOPMENT. Present-day ice nuclei instrument designs account for the fact that it may not be possible to reproduce primary ice formation processes exactly as they occur in the atmosphere, but assert that an instrument must reproduce some part of the range of temperature and relative humidity conditions present in and around clouds below 0°C. The capability to measure in the regime below water saturation where deposition nucleation and, at lower temperatures, heterogeneous or homogeneous haze particle freezing occur is critical because cirrus are climatically important. Hence, most new IN instruments can measure at controlled conditions below water saturation and, in some cases, well below −40°C. The other regime that requires measurements is at humidity in excess of water saturation where condensation and immersion freezing processes occur. Most new instruments are designed for this. Measurement of time-dependent contact-freezing nucleation presents a special challenge that has not been well met, especially in aircraftborne systems. Consequently, most of the IN measurement systems at ICIS-2007 focused on instantaneous IN dependence on temperature and RH and did not emphasize the detection of contact freezing.

The capability of all of the instruments operated at ICIS-2007 to measure ice nucleation across temperature and humidity space, combined with AIDA cloud formation experiments, provided important fundamental and practical insights. Precise control over key parameters permitted previously unattainable critical comparisons and can constrain modeling of the processes inside the instruments themselves. These are all steps taken toward facilitating the transposition of the instrumental data to cloud processes with a minimum number of assumptions and extrapolations.

Table 1 lists the ice nucleation instrument types used in ICIS-2007, while Table 2 compares the types of instruments used in the third and fourth workshops. The majority of the instruments at ICIS-2007 were of continuous flow diffusion chamber design, which has been responsible for most of the aircraft measurements of ice nuclei since the late 1990s (DeMott et al. 2010). All three CFDC types were represented, as well as a CFMC, two ISDCs, and an EDB operated to study immersion freezing of seeded drops. Additionally, AIDA cloud parcel expansions conducted at controlled slow pumping/cooling rates provided cloud particle residence times up to several minutes, which is more than an order of magnitude longer than all but the ISDC method.

Some details of the experimental plan, aerosol types, associated measurements of aerosol properties,

Table 1. ICIS-2007 ice nuclei instruments.

Instrument	Description	Type	Geometry	Reference
CSU CFDC-1H	Colorado State University CFDC-HIAPER version 1	Vertical (CFDC-2)	Cylindrical plates	Petters et al. (2009)
ZINC	Zurich Ice Nuclei Chamber	Vertical (CFDC-3)	Parallel plate	Stetzer et al. (2008)
FINCH	University of Frankfurt Fast Ice Nuclei Chamber	Vertical (CFMC)	Open cylinder	Bundke et al. (2008)
MRI CFDC	Meteorological Research Institute of Japan CFDC	Vertical (CFDC-2)	Cylindrical plates	—
MINC	University of Manchester CFDC	Vertical (CFDC-2)	Cylindrical plates	Jones et al. (2010)
Met Office CFDC	Met Office CFDC	Vertical (CFDC-2)	Cylindrical plates	—
UT CFDC	University of Toronto CFDC	Horizontal (CFDC-1)	Parallel plates	Kanji and Abbatt (2009)
UF FRIDGE TAUFRIDGE	University of Frankfurt Ice Deposition Freezing Experiment Tel Aviv University FRIDGE	ISDC	—	Bundke et al. (2008); Klein et al. (2010)
KIT AIDA	Karlsruhe Institute of Technology Aerosol Interactions and Dynamics in the Atmosphere	Controlled expansion cloud chamber	—	Möhler et al. (2006)
KIT EDB	Karlsruhe Institute of Technology Electrodynamic Balance	EDB	—	Duft and Leisner (2004)

Table 2. Portable ice nuclei instruments in international ice nucleation workshops.

IN device type	Third International Workshop (1975)	Fourth International Workshop (2007)
TGDC/ISDC	3	2
Diffusion or settling cloud chamber	2	0
Expansion cloud chamber	3	1
CFMC	0	1
CFDC	0	5
Other devices	2	1

and comparative results are given in Möhler et al. (2008), Koehler et al. (2010), Jones et al. (2011), and Kanji et al. (2011). Briefly, three aerosol types were produced as being representative of either known or potential atmospheric ice nuclei: surface-collected mineral dusts, soot particles, and ice nucleating bacteria. A few results are shown here to highlight advances for the measurement field.

Because newer devices are designed to precisely control the conditions of exposure of ice nuclei, we anticipated good agreement among the measurements. Indeed, Fig. 4 shows general agreement of Arizona Test Dust (ATD; Powder Technologies, Inc.) ice formation onset conditions between measurements made over wide temperature and relative humidity ranges. The results also validate previous studies that showed mineral dust particles typically require water saturation conditions for ice activation and show strongly diminished ice nucleus activity when warmer than –20°C. Note that no data are shown on this plot for conditions warmer than –17°C because the active fraction fell sharply below 0.1% of all particles freezing at this point. Differences between measurements are mostly within the measurement uncertainties for water relative humidity (RH_w), notably excepting some data from below –30°C, where the Zurich Ice Nucleation Chamber (ZINC) results deviated from others and there are no comparative AIDA parcel results. A possible reason for discrepancies is the fact that some instruments [Colorado State University (CSU), Met Office, and Manchester Ice Nucleus Chamber (MINC)] used upstream aerodynamic removal of larger particles (>1.5, 1.5, and 1.0 μm), while the ZINC instrument did not. Measured aerosol size distributions indicated that about 0.4% of all particles by number were at sizes above 1 μm, and at these low temperatures it is possible that the largest dust particles are the most active as ice nuclei at lower water relative humidities. Nevertheless, the University of Toronto (UT) CFDC and the University of Frankfurt (UF) FRIDGE instruments also did not use inlet impactors, yet agree with the other CFDCs. These low-temperature discrepancies were also not observed for polydisperse distributions of other dust particle types used in the workshop on other days (not shown here). The discrepancy with ZINC data thus remains unexplained at present. These types of issues demonstrate the utility of the comparative exercise for identifying where further work is needed.

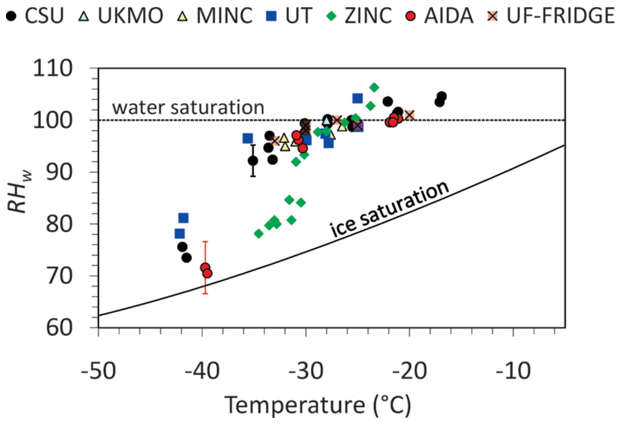

Fig. 4. Comparison of threshold ice formation (1 in 1,000 particles nucleating ice) conditions of a polydisperse distribution of ATD, as measured by the five CFDC instruments (CSU, UT, Met Office, MINC, and ZINC); the modified filter-processing device [UF FRIDGE: data collected after ICIS and reported by Klein et al. (2010)]; and in-cloud parcel simulations with the AIDA chamber. The ATD comparison was the most comprehensive of all ice nuclei aerosol types during ICIS-2007. Uncertainties in RH_w is shown for a single CSU CFDC data point, taken to be representative of most CFDCs, and a single AIDA cloud expansion data point.

The UF FRIDGE and the Tel Aviv University (TAU) FRIDGE both showed much lower concentrations of ice nuclei than any of the CFDC instruments during the workshop. A postanalysis of the measurements revealed that the petroleum jelly used to increase thermal contact between the collection filter and the cooling stage became mobile at the low pressure operational conditions and condensed on the ice nuclei, leading to a deactivation effect. Consequently, a new electrostatic sampling method was developed in which the aerosols are collected on silicon wafers that are not porous to thin layers of heat sink oil (Klein et al. 2010). Subsequent comparison of ice nuclei concentrations measured by both the UF FRIDGE and the TAU FRIDGE using this new sampling method showed excellent agreement with results from the Fast Ice Nuclei Chamber (FINCH) instrument.

Using this modified method, the UF FRIDGE sampled separate ATD samples that were generated and collected in the UF laboratory. These sample results are the data shown to be in good agreement with the majority of CFDC instrument results in Fig. 4, to as low as –33°C. This is an encouraging result, although the ATD particles in the later UF studies had a mode diameter of 0.8 versus 0.2 μm during ICIS studies, so future direct comparison is desired within the context of a formal workshop.

The Meteorological Research Institute (MRI) CFDC had thermal control issues during ICIS-2007, which limited the activated fraction to below 1 in 1,000 and led to a high offset of RH_w for activation. In the case of FINCH, fractional activation of ATD particles above 1 in 1,000 was also not achieved for conditions sampled during ICIS-2007. While not initially anticipated, these and other data collected for different aerosols ultimately demonstrated that the CFMC technique requires sample dilution in such comparative laboratory studies; too many aerosol particles lead to competition for the limited vapor supplied during mixing, which must both generate supersaturation and support growth of nucleated ice crystals. Consequently, detection saturates when ice nuclei concentrations reach somewhere around 100 L^{-1}. CFDC-type instruments include a continuous vapor supply and are not susceptible to counting saturation effects until ice nuclei concentrations exceed at least 1,000 cm^{-3} (Rogers 1988; Richardson 2009). The CFMC saturation limitation can be surmounted when natural ice nuclei concentrations exceed 100 L^{-1} by diluting the sample air; dilution necessarily lowers the effective sample volume advantage of this instrument.

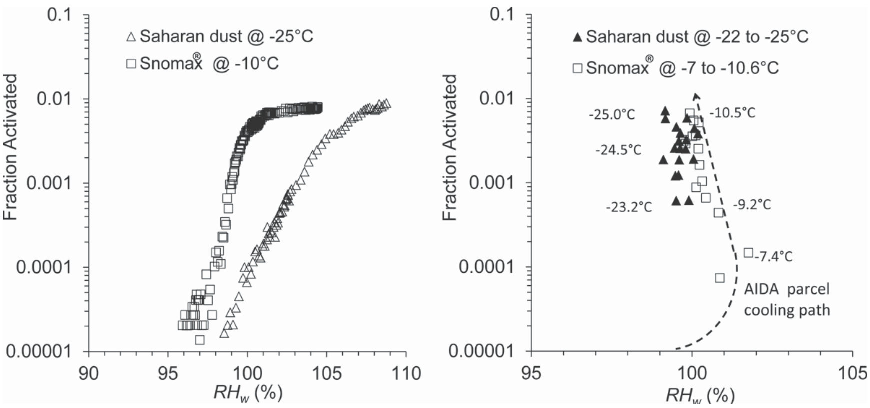

FIG. 5. (LEFT) Freezing fraction (with respect to total condensation nuclei numbers) of Saharan dust and Snomax bacteria particles during the slow increase of RH_w at the indicated nominal temperatures. (RIGHT) Freezing fractions of the same particles during cloud parcel experiments in AIDA, where the direction of cooling versus RH and fraction activated is shown for reference.

Experimental comparisons extended beyond the conditions required for the onset of ice formation need to account for differences in cloud parcel thermodynamic history between the IN devices and the cloud chamber. In AIDA the rate of pressure decrease during expansion is sufficient that RH_w initially rises transiently above 100% until all of the dust particles that do not immediately freeze are encapsulated in droplets that grow rather quickly beyond 10-μm diameter. Other particles freeze as the cloud cools during further slow expansion. The transient value of RH_w is not well defined at the point of cloud droplet activation, but it could be quite high for the pumping rates and particle concentrations used in these studies. In contrast, the mode of operation of ice nucleation instruments during ICIS-2007 was typically to scan RH_w from below to above water saturation over a narrow temperature range. The ice nucleation instruments must also achieve greater than the critical supersaturation for droplet activation to ensure that all of the dust particles enter droplets and have the ability to freeze in a manner similar to the AIDA expansions. RH_w uncertainties of up to 3% in CFDC instruments operating at lower temperatures suggest that greater than 103% RH_w may be necessary to ensure droplet activation (DeMott et al. 2009). Once droplets form, their growth is limited by the relatively short residence times in the ice nuclei instruments. Petters et al. (2009) inferred that, as a consequence, ice nucleating particles produced from burning biomass required RH_w in excess of 105% to become large enough and dilute enough to overcome surface chemical impacts on ice nucleation that are present at small droplet sizes following activation as CCN. Similar influences of short residence time and possible chemical effects were noted for dust ice nuclei during ICIS, as shown for the freezing of Saharan dust particles in the CSU CFDC in Fig. 5a. Above 105% RH_w, where drop activation and rapid dilution of any impurities is most likely, freezing fractions typically increased by less than a factor of 2 for any of the dust particles sampled by the CSU instrument during ICIS. In contrast to dust ice nuclei, bacterial ice nuclei achieved their maximum fraction of ice activation over very narrow RH_w regimes (Fig. 5a), much as was observed for a homogeneous freezing process in a CFDC (Richardson et al. 2010). This may relate to the fact that bacteria possess more uniform surface physical and chemical properties with regard to water uptake and ice nucleation. Assuming that maximum active fraction is the parameter used for comparison on the basis of the discussion above, Fig. 5b shows that similar fractions are activated at a given temperature for the Saharan dust particles or for the Snomax bacteria particles in AIDA and the CSU CFDC. This discussion also suggests that a capability to control supersaturation to the degree possible in CCN instruments, which is not presently possible in ice nuclei instruments, may not be sufficient for resolving the limitation on freezing that may be imposed by the CCN activation process at typical atmospheric supersaturations (e.g., below ~1% supersaturation). It seems feasible only to define the maximum freezing fractions occurring in the supersaturated regime, which is the approach taken in some previous studies (DeMott et al. 1998; Petters et al. 2009; Prenni et al. 2009b).

Figure 6 shows an example of ice active fraction results from a large number of experiments performed over a broad temperature range for the Saharan dust sample used in ICIS-2007. Data from several AIDA experiments are shown following the cooling history after clouds formed. We have restricted the reported data from selected portable instruments to RH_w in 2% increments both at and above 102% (to 110%), and the relative increases in activated fraction versus RH_w is understood in the context of the previous discussion and the results shown in Fig. 5. Thus, we expect that supersaturation above 105% RH_w in the flow chambers promote formation of larger droplets and faster dilution of soluble surface impurities, presumably in better equivalence to droplets formed over longer growth times in AIDA. In this way it is possible to find agreement in activated particle fraction between fast ice nuclei instruments and the AIDA chamber over their overlapping range of mixed-phase cloud conditions. Nevertheless, we note that there remains a spread of four to five in active fraction between individual instruments at single RH_w values above 102%. Additionally, the change in active fraction with RH_w differs for different instruments. While the source of these discrepancies remains to be fully explored, we speculate that this relates to differences in instrument residence times and thermodynamic histories affecting droplet growth and evaporation. For example, while the geometry of the cylindrical CFDC instruments was similar in ICIS-2007, they were configured differently in their lower sections for evaporating droplets, as required for the optical detection of ice. The evaporation regions of the MINC and Met Office instruments as configured for ICIS-2007 employed one ice-coated cold wall and a dry, insulated warm wall, equivalent to the design of the original aircraft version of the CSU CFDC (Rogers et al. 2001). The CSU CFDC-HAIPER version 1 (1H) uses ice surfaces throughout, controlling both walls equal in temperature to the colder (inner) wall condition in the lowest third of the chamber. This may slow the evaporation kinetics of activated droplets and assist in identifying the smallest activated ice crystals in the CSU instrument compared to the other devices.

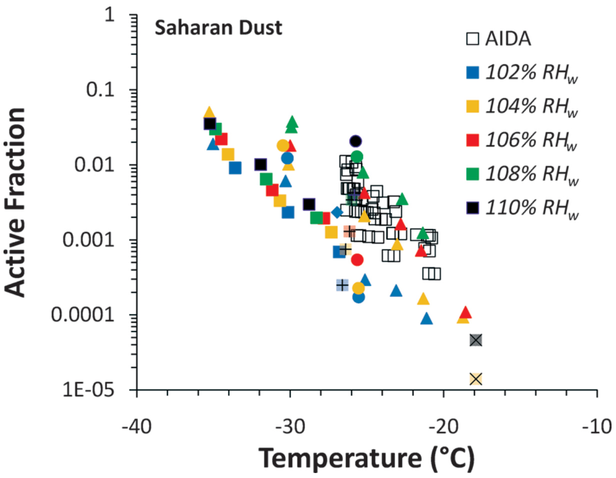

Fig. 6. Comparison of the IN active fractions (see text) versus temperature of a Saharan dust aerosol distribution, color coded by processing water RH, as measured by seven methods. Symbols indicate the continuous flow diffusion chambers ZINC (■), CSU (▲), UT (◆), MINC (•), and UKMO (+) (see Table 1), the continuous flow mixing chamber FINCH (X), and the AIDA cloud simulations (□).

The ZINC instrument possessed the longest growth and evaporation sections and also active cooling control of ice surfaces in its evaporation section. The longer evaporation section of the ZINC instrument also permits extension of measurements to a higher water supersaturation bound before water droplets begin to survive through to the optical detector (Nicolet et al. 2010). However, the ZINC evaporation section also controls temperature to equate to the warm ice wall condition rather than the cold wall. This perhaps influences the narrower spread of activated fractions as a function of RH_w in excess of water saturation in the ZINC instrument (Fig. 6). Evidence that these instrument differences affect the detection of ice nuclei concentrations, especially in the condensation/immersion freezing regime above water saturation, illuminates the need for future detailed experimental and numerical modeling studies of the thermodynamic and microphysical processes that are at play. These factors additionally motivate development of detectors for discriminating particle phase (liquid vs ice) independent of sizing.

SUMMARY AND CONCLUSIONS.

Construction of new portable systems for measuring ice nuclei in the atmosphere over the last five years (see Table 1), along with noted increases in publications of laboratory, numerical modeling, and field measurements of ice nucleation point to the present vitality of this research field. Advances in this area are being stimulated and evaluated through a revival of workshops on ice nucleation measurement. New results indicate a growing level of consistency among, and an understanding of differences between, different measurement methods for ice nuclei, which is providing new confidence in measurement capabilities for detecting the atmospheric variability and dependencies of ice nucleation to frame our understanding of ice formation in clouds. Clear and significant research issues remain, most notably the need to make measurements at temperatures above –15°C. Nonetheless, we expect that further instrumentation developments, workshop assessment activities, and improved quantitative data on atmospheric ice nuclei populations will be coming in the near future.

ACKNOWLEDGMENTS. The lead author and MDP acknowledge support from the U.S. National Science Foundation Grants ATM-0611936 and ATM-0841602. Karlsruhe Institute of Technology provided funding during ICIS-2007 for the facility infrastructure within the Helmholtz Research Programme "Atmosphere and Climate." The European Science Foundation's INTROP program supported an ICIS data workshop in Pontresina, Switzerland, in 2008. The European ACCENT program financially supported Eli Ganor, Masataka Murakami, Atsushi Saito, and Hazel Jones for participating in ICIS-2007. The University of Toronto Centre for Global Change Science (CGCS) scholarship and the Natural Sciences and Engineering Research Council of Canada (NSERC) financially supported Zamin Kanji for participating in ICIS-2007. The analysis of the data at Tel Aviv University and at the University of Frankfurt was carried out under the partial support of grants from the Virtual Institute on Aerosol Cloud Interactions, supported by the Helmholtz Gemeinschaft (HGF) and by the German-Israeli Foundation (GIF) Grant 186027. We gratefully acknowledge skillful support from the AIDA team for organizational issues, instrument setup, and AIDA chamber operation during the ICIS-2007 experiments. We also thank Thomas Schwartz from the Institut für Technische Chemie of Karlsruhe Institute of Technology for support in preparing the bacterial cultures.

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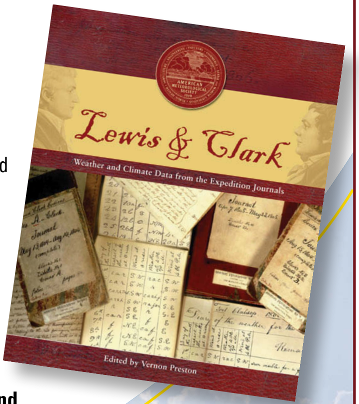
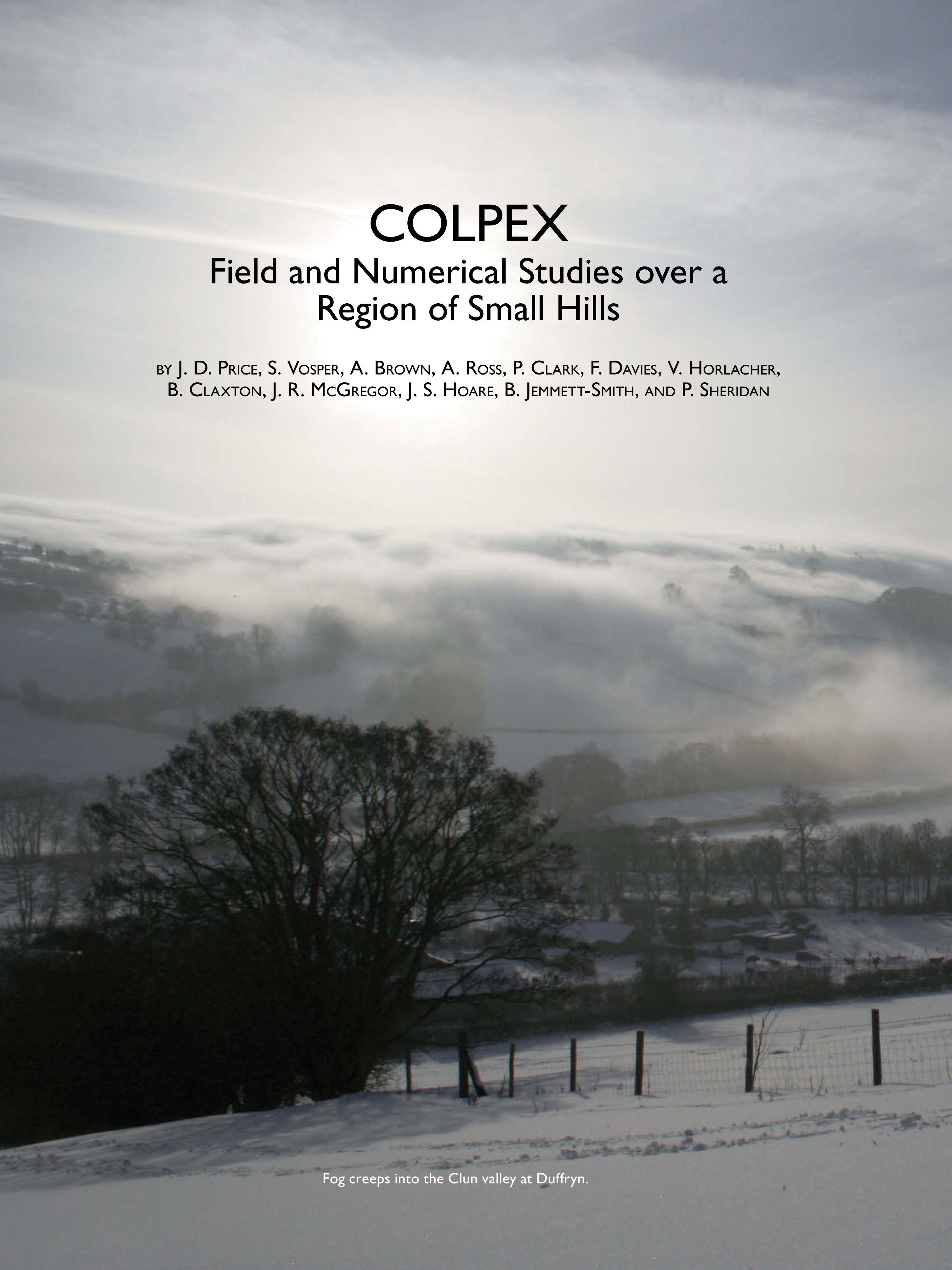


COLPEX

Field and Numerical Studies over a Region of Small Hills

by J. D. Price, S. Vosper, A. Brown, A. Ross, P. Clark, F. Davies, V. Horlacher, B. Claxton, J. R. McGregor, J. S. Hoare, B. Jemmett-Smith, and P. Sheridan



Fog creeps into the Clun valley at Duffryn.

In the low (up to 100 m) hills and narrow (1–3 km wide) valleys of Shropshire, atmospheric conditions—including cold-air pooling and fog—can range widely over such short distances that they escape the attention of numerical forecast models.

Large variations in near-surface temperature associated with stable nighttime conditions are known to occur over complex terrain. These variations are often associated with adverse economic and safety impacts. For example, pooling of cold air in a valley may lead to localized ice on roads, even when most roads in the region are above freezing, which is hazardous if not treated. Localized frosts can also have a significant impact on agriculture through damage to crops. Furthermore, lower temperatures will increase relative humidity and enhance fog formation in many valley locations, with impacts on road safety and aviation. Cold pooling may also lead to trapping of pollutants, with resulting health implications. In addition to these local effects on temperature and fog formation, the mixing and transport processes occurring in complex terrain can impact the larger-scale flow and so there is a need to correctly parameterize these processes in coarse-resolution weather forecasting and climate models. Such errors may be responsible for observed cold biases over complex terrain in some models (Sheridan et al. 2010). The large observed temperature variations in cold pools mean that ▶

changes in the frequency and magnitude of cold-air pooling during a period of changing climate could potentially alter climate statistics for that region (Daly et al. 2010).

In spite of the strong motivation to be able to provide accurate predictions of local conditions in such regions, the problem remains hugely challenging. In part, this is because current numerical weather prediction (NWP) models, which form the cornerstone of most modern forecasting systems, usually do not have sufficiently fine grid spacing to be able to represent the crucial local topographic variations. In moderate-scale valleys, these variations may be on horizontal scales of hundreds of meters, whereas even the most advanced operational NWP models may have resolutions of 1–2 km at best. In addition, there also remain significant uncertainties surrounding the key processes involved. Even in the absence of significant surface heterogeneity, surface and near-surface temperatures in light-wind stable conditions are strongly sensitive to the details of the surface energy balance and in particular to the strength of turbulent mixing. In a region of hills, the situation is further complicated by topography where we often see cold-air pools in valleys and warmer air over the hilltops. In mountainous regions, the presence of cold-air pools in valleys has often been attributed to the nocturnal drainage of cold-air down valley sides (“drainage currents”; e.g., Rotach et al. 2008). However, a further mechanism that is thought to be important for smaller-scale valleys such as the ones studied during COLPEX involves sheltering of the valleys by the surrounding hills. This produces low levels of turbulence in the valleys allowing radiative cooling to create a local pool of cold air there. In regions that are not sheltered (e.g., the hilltops), turbulence continues for longer into the night, offsetting and reducing the effect of radiative cooling and keeping temperatures there warmer. There is some evidence from observations (Gustavsson and Bogren 1995) and idealized modeling (Vosper and Brown 2008) to support this mechanism. Quantifying the relative importance of these different sources of cold air in regions of small hills remains a significant challenge for numerical modeling (e.g., Vosper and Brown 2008).

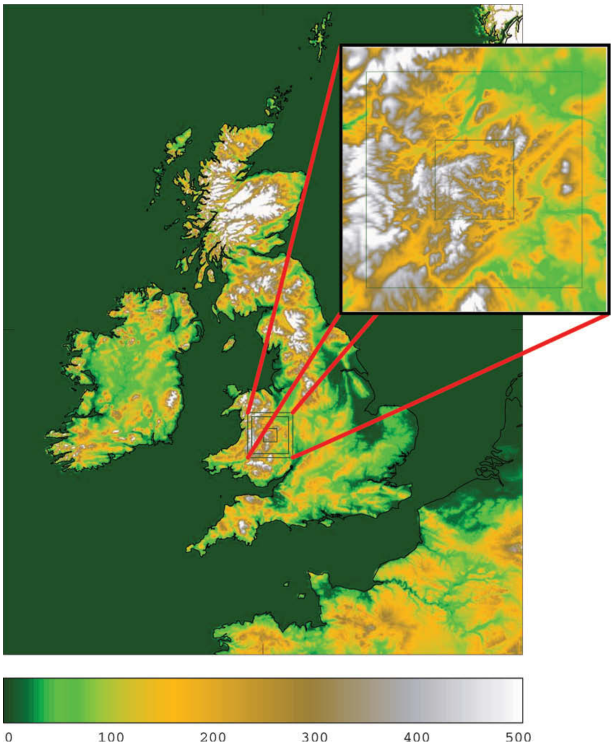


Fig. 1. Map of the United Kingdom showing the experimental region on the border between Wales and England and the nesting of the Met Office 1.5-km-resolution model. Inset is the orography in the model domain; the innermost square has horizontal resolution of 100 m; in the next square, resolution varies continuously up to 1.5 km at the next square boundary.

Previous observational and modeling studies of the stable boundary layer over complex terrain have usually focused on regions with large-scale orography: for example, the Mesoscale Alpine Programme (MAP) Riviera project (Rotach et al. 2004, 2008) and the Vertical Transport and Mixing (VTMX) experiment (Doran et al. 2002). Smith et al. (2010) compared model results against observations on scales of approximately 50 km. The recent Meteor Crater Experiment (METCRAX; Whiteman et al. 2008) studied pooling in a meteor crater that is more comparable in scale to the valleys we are interested in, but the confined bowl geometry (and very dry climate) makes it quite different to many typical mid-latitude valleys. Therefore, to gain more information

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/2011BAMS-D-10-3032.1

In final form 12 July 2011

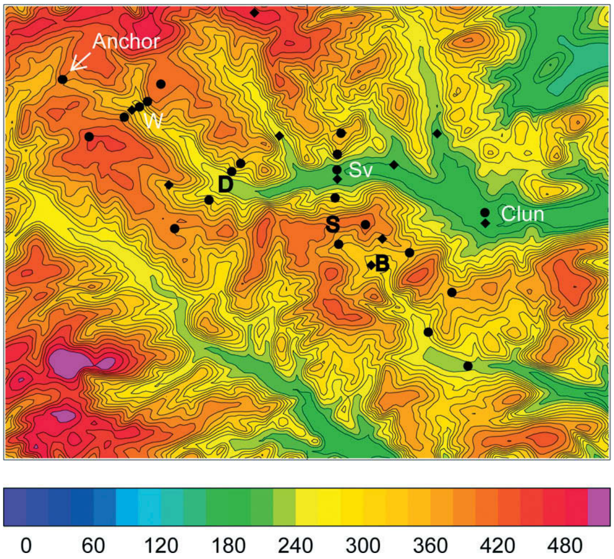

Fig. 2. Map of the experimental area showing locations of weather stations. The area depicted is 18 km (west to east) by 13 km (north to south) and oriented north upward along the y axis. Main sites are marked by letter: D for Duffryn, S for Springhill, and B for Burfield. Circles denote approximate locations of HOBO weather stations and diamonds denote approximate locations of University of Leeds automatic weather stations. Sv marks the Springhill valley site and W marks the Weals House. Contours and colors are altitude above mean sea level (meters).

about such regions we have designed and carried out the Cold-Air Pooling Experiment (COLPEX). The campaign has both a field experiment and a modeling component, with the former providing a framework and dataset for the latter. The experimental phase ran between January 2009 and April 2010. The main aims of COLPEX can be summarized as follows:

- Collect a large dataset with good spatial coverage representative of conditions in a region of small hills, over a seasonal time scale (15 months).
- Analyze data on both seasonal and case-study time scales.
- Elucidate the main mechanisms responsible for formation of cold-air pools in this type of orography.
- Examine and improve the performance of high-resolution numerical model simulation of cold pools.
- Improve the representation of small-scale cold-pool processes in coarser-resolution operational models and refine downscaling techniques to forecast small-scale variability in near-surface temperatures.
- Study the formation of fog in cold pools.
- Examine and improve the performance of high-resolution models simulating fog.

In this study, a distinction is made between local and nonlocal processes, with the intention to primarily study the former. The term "drainage flow" is used to describe local winds forming within a valley system, whereas nonlocal drainage winds entering the valley will be referred to as gravity currents.

LOCATION, INSTRUMENTATION, AND SETUP. COLPEX was located in a region of small hills on the border between England and Wales in the central United Kingdom, centered on 52°25′56″N, 3°08′42″W (see Fig. 1). Typical valley widths (peak to peak) are on the order of 1–3 km, and ridge to floor heights are 75–150 m. The instrumentation deployed during COLPEX falls into two categories: that deployed at three main sites and other equipment in a series of small satellite stations surrounding the main sites. The aim of this configuration was to obtain detailed information at three important locations in the region, with the surrounding stations providing less detailed observations, which could place those made at the main sites into a wider context. Figure 2 shows a map of the region with the locations of the weather stations. Figure 3 displays a photograph of the main Clun Valley (containing Duffryn). It can be seen that land coverage is mostly pasture and hedgerows, with some woodland (<10%). The Burfield valley to the south is more open, with fewer hedges and trees.

Fig. 3. View of the Clun valley taken from the ridge to its south approximately 1.5 km west of Springhill, looking northeastward. The Springhill cross section is in the middle ground (see text).

The three main sites were chosen to examine conditions in the larger, relatively deep and narrow valley (Duffryn); the second shallower, bowl-shaped valley (Burfield); and a ridge top (Springhill). The valleys were located next to each other separated by the ridge-top site at Springhill. This allowed a detailed comparison of cold pooling and fog formation in the two different topologies of valley and the ridge-top conditions for each. A characteristic of the two valleys is that neither has a large upstream catchment; for Duffryn, it is approximately 5.5 km to the valley head, and the bowl at Burfield is effectively the valley head. The surrounding land rises to narrow ridges so that there are no large upland areas that can drain into these valleys. This means that (in the absence of synoptic-scale influences) conditions measured in them will be of local origin, which will better allow us to understand the role of local processes in cold-air pooling. The instrumentation deployed at the three main sites is detailed in Table 1. Much of this was based around a main tower deployed at each site (50 m high at Duffryn and 30 m at Springhill and Burfield). Duffryn and Springhill were powered from mains electricity supply (grid power), and the site at Burfield was powered via an autonomous (off grid) supply developed by the Met Office. This consisted of a bank of 12-volt lead acid batteries (600 amp hours) charged by a combination of solar panels and a wind generator to supply a continuous 3.5–4.0 amps at 12 volts. When the power from these is insufficient, a propane generator automatically cuts in to charge the batteries (taking approximately 6 h). A photograph of the main site at Duffryn is shown in Fig. 4.

Data at the three main sites were collected either on a DataTaker datalogger for screen level (1.2 m) and radiation measurements or a Moxa minicomputer for mast mounted instruments. The latter were logged at 10-Hz frequency, allowing turbulent fluxes to be calculated. Internet and mobile phone links were used to monitor these sites remotely for quality control checks, though retrieval of the full datasets was performed by hand because of bandwidth and other limitations with the connections. The measurements collected at these sites in principle allow the energy balance to be calculated. The main site at Duffryn benefited from a Halo Photonics Doppler lidar and Hatpro microwave radiometer, funded by the Facility for Ground-based Atmospheric Measurements

Table 1. Summary of equipment deployed at the three main sites during COLPEX, with height or depth marked.

	Duffryn	Springhill	Burfield
Wind (Gill HS50 sonic anemometers)	50, 25, 10, and 2 m	30 and 10 m	30 and 10 m
Temperature (platinum resistance)	50, 25, 10, and 1.2 m	30, 10, and 1.2 m	30, 10, and 1.2 m
Infrared canopy temperature (Heitronics KT15–2)	Yes	Yes	Yes
Humidity (Humicap)	50, 25, 10,* and 1.2 m	30, 10, and 1.2 m	30, 10, and 1.2 m
Soil temperature and heat flux plate (Hukseflux HFP01-sc)	3-cm depth	3-cm depth	3-cm depth
Visibility (Biral HSSVPF-730 present weather sensor)	2 m	2 m	—
Radiation Kipp & Zonenen CG4, CM21, and CNR2 net	2 m: longwave up (LWUP), longwave down (LWDN), shortwave up (SWUP), and shortwave down (SWDN) 50 m: net longwave (LW) and net shortwave (SW)	2 m: LWUP, LWDN, SWUP, and SWDN	2 m: LWUP, LWDN, SWUP, and SWDN
Other instrumentation	Pressure, soil moisture, Halo Photonics Doppler lidar, and Hatpro RPG microwave radiometer		
Deployed during IOP	Radiosondes, TSI AM510 aerosol monitor (3 m), TSI CPC3007 particle counter (3 m), DMT cloud droplet probe (2 m)	Radiosondes**	Radiosondes**

* Also includes a Licor Li7500 at 10 m.

** At one site or the other only.

(FGAM) within the National Centre for Atmospheric Science (NCAS).

The surrounding station instrumentation was of two types: 10 stations were designed and built by the University of Leeds, which included sensors for wind (at 2 m), pressure, temperature, relative humidity (1.5 m), and soil temperature (3-cm depth). Power was supplied from solar panels. The wind measurement is made with a Gill Instruments 2D sonic anemometer, which gives good performance in low wind speeds. A further 21 stations were HOBO dataloggers (Onsett Computing, Inc.) with temperature and humidity measurements made at between 1.2 and 2.5 m (some sensors had to be placed out of reach of livestock). One station also included wind and pressure measurement. A number of HOBO stations were set out in lines aimed at giving a crude cross section of data through three sections of the main valley. These were the Weals House (between Duffryn and Anchor), Duffryn, and Springhill cross sections (see Fig. 2). The rest of the stations were spread around to give a representative sample of conditions in the locality. Data from these devices were stored locally on their dataloggers and collected by hand approximately every 6 weeks. Figure 5 shows a typical HOBO installation.

Additional instrumentation was deployed for intensive observation periods (IOPs), as listed in Table 1. This included two radiosonde stations: one of which operated from Duffryn and the other operated from either Springhill or Burfield. Typically 8–10 radiosondes were launched from each site during a night to morning period at intervals between 1 and 1½ h.

INITIAL RESULTS. *Climatology for the period.*

The climatological conditions experienced during the COLPEX campaign consisted of a warmer but wetter than average summer and a colder than average winter. Summer conditions resulted in fewer clear radiation nights than usual, which are the periods of most interest for cold-pool formation. Despite this, 10 IOPs were conducted by autumn. The winter period started cold and wet and continued cold with snow. The amounts of snowfall were much larger than usual for the area (indeed, this was the case over much of

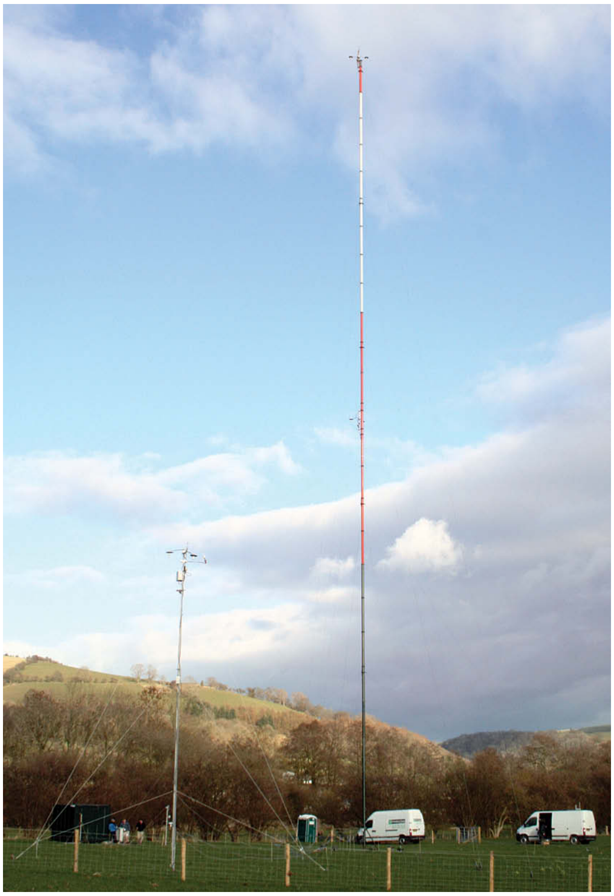

Fig. 4. The 10-m and 50-m masts at Upper Duffryn main site.

Fig. 5. Putting the final touches to a HOBO installation before getting a soaking!

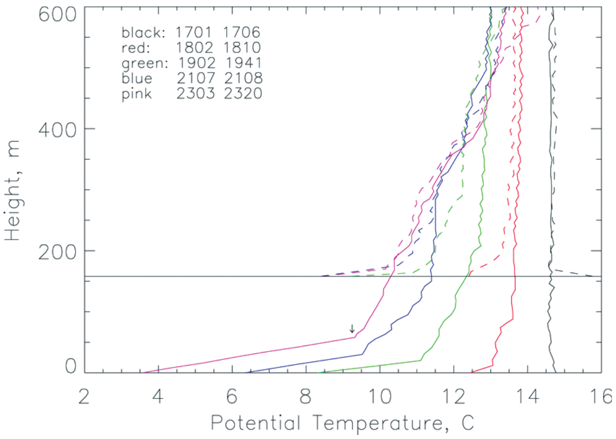

Fig. 6. Potential temperature profiles from radiosonde data at Duffryn (solid lines) and Springhill (dashed lines) for 9 Sep 2009. Heights are above ground level at Duffryn. The level of the Springhill site is marked by the horizontal line at 160 m.

the country) and caused significant logistical problems maintaining equipment, as well as reducing the number of IOPs conducted over the winter months. In particular, the Burfield site was effectively cut off for several weeks over the Christmas and New Year period, which unfortunately resulted in episodic loss of data. A further seven IOPs were conducted over the winter and spring period.

Intensive observation periods. Two IOPs are presented here as examples of the data collected during COLPEX. Some data from the weather station network for January 2010 are also presented. The first case study occurred on 9–10 September 2009 and was characterized by a late-summer high pressure system with light winds and some cumulus cloud during the daytime. This was followed by a clear night, allowing radiative cooling to dominate the boundary layer evolution. The second case study occurred on 16–17 September, which was also characterized by high pressure and light winds but with significant amounts of stratocumulus cloud, which prevented a significant stable boundary layer forming. The second case is presented as a contrast to the first.

Figure 6 shows potential temperature profiles for 9 September 2009 measured by radiosondes released at the Duffryn valley and Springhill ridge-top sites. The cooling rates and vertical stability structure are evident in this plot. Note the early cooling while the atmosphere was still adiabatic (profiles to 1810 UTC) appears to be caused by a larger-scale advection. Later profiles show the characteristic structure of stable boundary layer development. However, note that the inversion at Springhill is significantly weaker and shallower than that at Duffryn and that profiles from the two sites are very similar from about 40 m above the Springhill site. Also notable, particularly at Duffryn, is the very linear profile next to the ground and sharp discontinuity in stability at its top (marked with a small arrow for the 2303 UTC ascent). It is possible that this feature may be connected with the cold-pooling process, although it is noted that similar profiles are sometimes seen at sites with much flatter orography where limited cold pooling might be

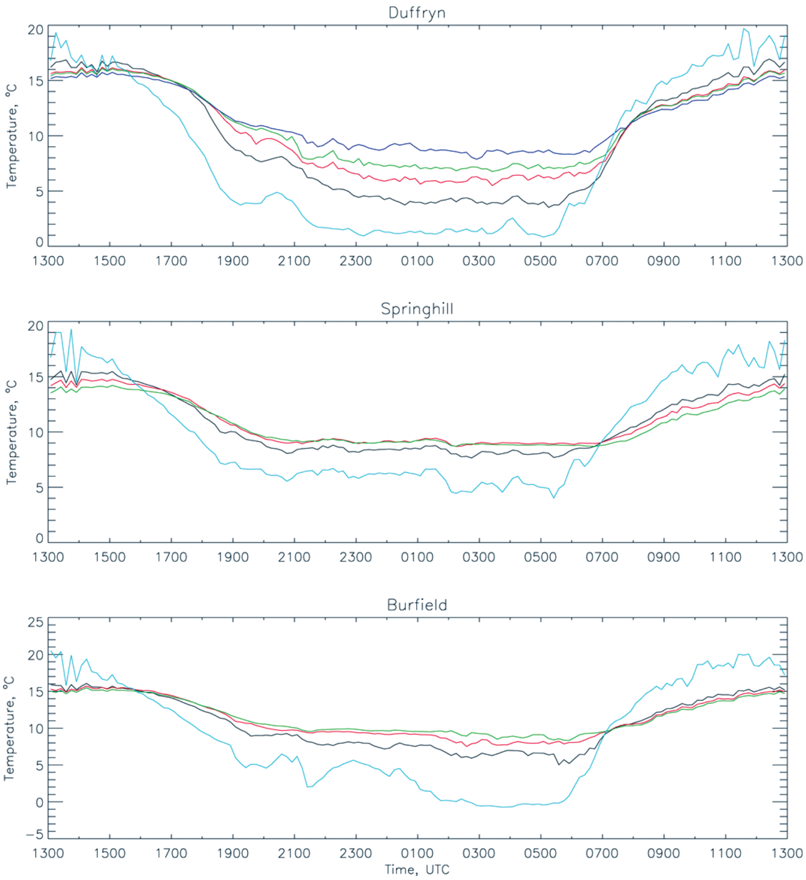

Fig. 7. Temperature evolution at the three main sites for 9–10 Sep 2009. Lines are at the following levels: black is 1.2 m, red is 10 m, green is 25 m (Duffryn) and 30 m (Burfield and Springhill), dark blue is 50 m, and light blue is infrared surface measurement.

expected (see, e.g., Edwards et al. 2006), and therefore their origin is presently uncertain.

Figure 7 shows temperature evolution from the mast mounted sensors at the three main sites for 9–10 September 2009. Figure 8 shows the same plot but for 16–17 September. In these plots, a judgment of stability can be made by considering the distance between the individual temperature traces. Comparing the two diagrams illustrates the very different structure seen on radiation nights, compared to cloudy ones. For 9 September, there is a marked transition during early evening (around 1600–1700 UTC) from unstable or neutral conditions to stable, because the temperatures cool relatively quickly and diverge at the different levels. The effect is greatest at the main site in the Duffryn valley and least on the ridge top at Springhill. At the former, the temperature inversion is strong and deep, extending above 50 m (see Fig. 6). At Springhill, the inversion is shallow and weak, not extending significantly above 10 m. Note that, after the initial rapid cooling, temperatures remained relatively stable with only a little further cooling. The minimal stable boundary layer seen on the hilltop is interesting and may be due to the higher levels of turbulence maintained there. However, another mechanism that would act to limit the stable conditions on the hilltops is if air there drains slowly away into the valleys, preventing the buildup of a deep inversion. The different stabilities in the two valleys are also interesting: Despite its valley location, the Burfield site temperature structure appears more similar to the hilltop conditions for this night, and the inversion there appears weak. This may indicate that the Burfield site was less sheltered than the Duffryn site.

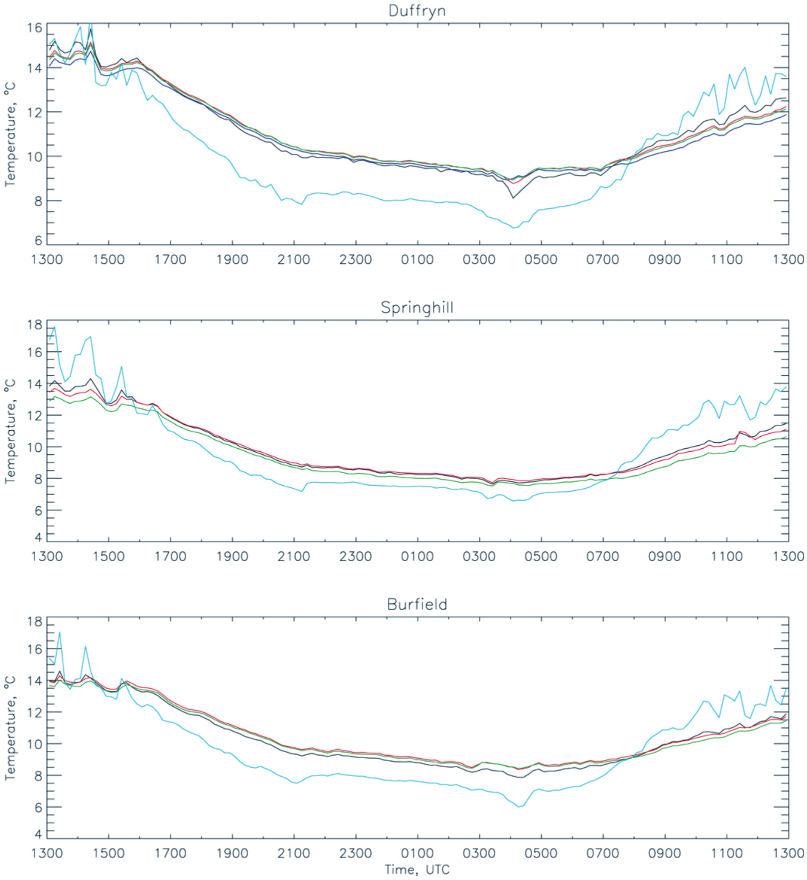

Fig. 8. As in Fig. 5, but for 16–17 Sep 2009.

In contrast, Fig. 8 shows a much less marked transition during the evening. In fact only the surface to screen level shows a significant inversion. The other levels show a lapse rate close to adiabatic. Cooling rates during the early period are also reduced. For example, the maximum cooling rate at screen level (1.2 m) for Duffryn on 9 September was 4.2°C h^{-1}, whereas on 16 September it was only 1.9°C h^{-1}. Note that the variation in surface temperature during the day on these days is caused by the partially cloudy skies present then.

Figure 9 shows the sensible heat fluxes measured with mast mounted sonic anemometers. These show the normal evolution of positive fluxes during the day, which reverse at the transition and reach a negative maximum some 2–4 h later and then tend toward zero as levels of turbulence decreased in the increasingly stable surface layer. This happens first at Duffryn, where stability increases quickest and becomes greatest. The higher fluxes seen at Burfield may be the reason why the cold pool there remained warmer and less stable than at Duffryn (Fig. 7). Note that, on the ridge top at Springhill, fluxes remain negative until the morning transition (0700 UTC 9 September). Also note there that, at 30 m, where conditions are near neutral (see Fig. 6), there was no significant negative peak after the evening transition. Values of vertical velocity variance (not shown) showed that turbulence levels at 10 and 30 m remained significantly higher at Springhill throughout the night than at the other two sites. Figure 10 is similar to Fig. 9, but

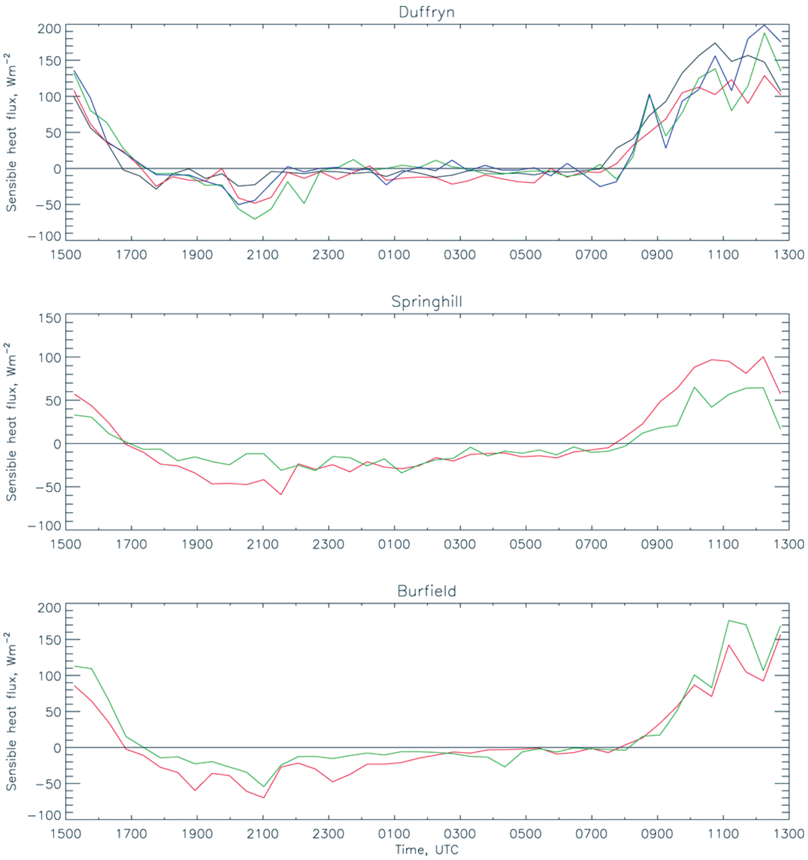

FIG. 9. Sensible heat fluxes for 9–10 Sep 2009. Lines are at the following levels: black is 2 m, red is 10 m, green is 25 m (Duffryn) and 30 m (Burfield and Springhill), and dark blue is 50 m.

for 16–17 September. Heat fluxes still go negative at the transition and show a negative peak shortly after (though rather indistinct), but values are approximately half of those seen on 9–10 September. Note also that fluxes at all sites remain significantly below zero until the morning transition. Analysis of vertical velocity variance (not shown) was consistent with this result, indicating that turbulence levels remained higher throughout the night on 16–17 September.

To demonstrate the magnitude and frequency of small-scale variations in near-surface temperature experienced in the COLPEX region during the experiment, a bar chart depicting the frequency of different sized deviations of screen temperatures at the valley mast sites (Duffryn and Burfield) from a reference given by the 30-m temperature at Springhill is shown in Fig. 11. The coldest (relative to Springhill) overnight valley temperature was used in order to emphasize the peak intensity of any cold pool. Here, "overnight" indicates 24 h centered on 0000 UTC; only periods where more than 50% of data were flagged with suitable data quality were used, totaling 274 nights for Burfield and 263 nights for Duffryn.

For both valleys, there is a clear peak near the adiabatic lapse rate (small negative values), indicating nights dominated by well-mixed conditions. However, temperature inversions occur on most nights, with strong inversions ≥ 4°C between the hilltop and valley recorded on 25% of nights for Duffryn and 15% for Burfield and very strong inversions ≥ 6°C on 6% of nights for Duffryn and 3% of nights for Burfield. The smaller numbers for Burfield may reflect the smaller height difference with respect to Springhill but also that the site is less sheltered than Duffryn and thus experiences more turbulent heating as discussed above. Figure 11 is indicative of the degree of subgrid-scale variability that is likely to go unrepresented in a forecast over terrain of this kind. Previous work by Sheridan et al. (2010) showed that a simple extrapolation technique based on altitude together with an estimate of lapse rate could be used to predict subgrid variations. Their scheme, however, does not account for valley flow processes such as sheltering by surrounding terrain, which are expected to be active in generating the cold extremes seen in these small valleys. As a consequence, many of the lapse rates indicated by Fig. 11 are considerably more stable than those typically used in the extrapolation technique described above. The valley flow dynamics revealed by COLPEX will form the basis for development of more advanced techniques.

Weather station network. Next, a sample of results from the network of small weather stations deployed in the COLEPX region is presented. This dataset allows the spatial distribution of cold pools to be examined. Figure 12 shows time series of stations from the main valley floor at various positions along its length, for a few days during January 2010. This month was cloudier than the seasonal average for this time of year, and stable boundary layers formed on less than half the nights, but it was also colder so that when stable boundary layers formed they were often very cold. Figure 12 shows a period when the coldest temperatures were recorded during COLPEX, on 7 and

Fig. 10. As in Fig. 7, but for 16–17 Sep 2009.

8 September, when temperatures reached −18.4°C. The colder negative spikes illustrate the formation of the stable boundary layers and cold pools. Note that the trace for Clun Castle (red) is consistently the coldest on these nights and that the trace for Anchor (black) is the warmest on stable nights. The site near Clun Castle is the lowest elevation and farthest down the valley, whereas Anchor is at the highest elevation at the top of the valley (almost level with the surrounding hilltops). The two other sites are between these, with the green trace being the farthest down the valley and generally showing colder temperatures on stable nights than the blue trace farther up the valley (see Fig. 2 for locations). Thus, the results for stable nights consistently show increasingly colder temperatures as one travels down the valley. This is consistent with cold pooling via a slow drainage flow, which remains in near equilibrium with the radiative cooling, but not necessarily with a cold gravity current, which one might expect to warm adiabatically as it moved down the valley (see later discussion in the summary). Also interesting in this plot is the night of 8–9 January 2010. Here, we see that a cold pool started forming early on 8 January but rapidly disappeared around midnight and then reappeared in the early hours of 9 January. The interlude of near-neutral conditions between approximately 2000 UTC 8 January and 0500 UTC 9 January was caused by the appearance of a layer of stratus. The rapid change in conditions seen at the surface is quite striking, and the rapid return to stable conditions when the cloud partially cleared after 0500 UTC is also surprising. It can also be noted from Fig. 12 that, for generally cloudy conditions, including the period from 10 January onward, no cold pool forms, and we see the opposite temperature structure, with colder temperatures higher up the valley, which is in accordance with the general adiabatic lapse rate in these conditions. The presence of low cloud during

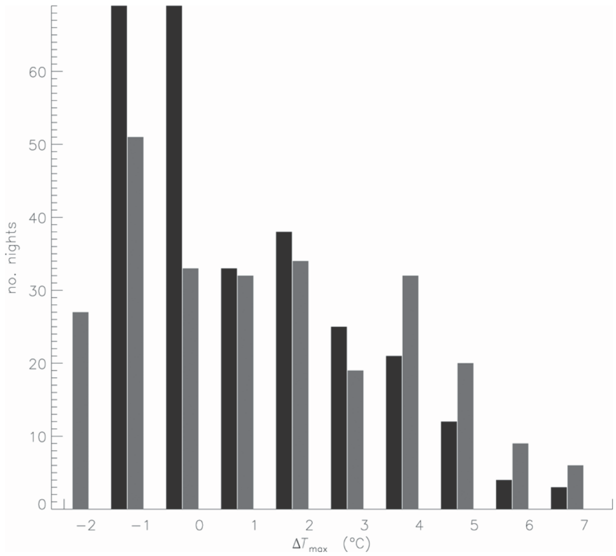

Fig. 11. Bar chart showing the number of nights in different 1°C ranges of ΔT_{max}, the maximum overnight value of [T_Springhill(30 m) – T_valley(1.2 m)], where T_valley(1.2 m) corresponds to the Burfield mast (black) or the Duffryn mast (grey). Here, 10-min-average temperature data have been used. Bars are labeled on the *x* axis showing the minimum of the range corresponding to the bar.

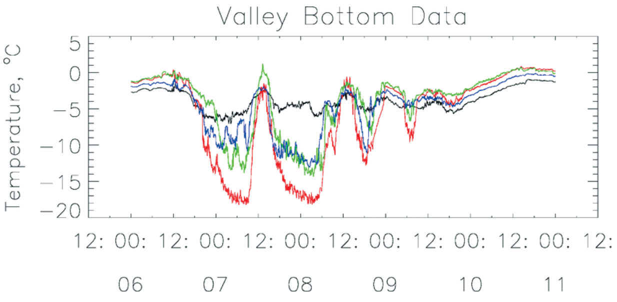

Fig. 12. Time series of temperature in the main Clun valley at four locations for January 2010. Lines represent the following locations: black is Anchor, blue is Weals House, green is Springhill valley, and red is Clun Castle. See Fig. 2 for locations.

cold-pool evolution can be confirmed with lidar data. A Halo Photonics streamline Doppler lidar was located at the Duffryn site. This device detects aerosol, cloud droplets, and precipitation in the boundary layer and calculates radial velocity via the Doppler principle. The system is a 1.5-micron pulsed lidar with a range resolution of 30 m and has a full hemispheric scanning capability. A full description of the instrument and its characteristics can be found in Pearson et al. (2009). Most data were taken with a vertical beam, which allows cloud-base detection and vertical velocity measurement. Data confirm the presence of cloud for the cold-pool erosion seen in Fig. 12. However, for that case, precipitation below cloud contaminated the vertical velocity measurement. A similar case is presented in Fig. 13, which shows the interruption of a clear-sky cold-pool episode by a layer of stratocumulus and the change in the velocity field at its arrival. The top panel shows vertical velocity, which indicates convective activity up to about 1900 UTC. After this, activity decreases for several hours up until about 26 h (0300 UTC 11 February). During this nighttime period, a stable boundary layer formed. However, at 26 h, convective activity increases again, more so in the upper part of the boundary layer. The bottom panel shows lidar backscatter, where red, orange, and yellow colors indicate cloud and green and blue indicate aerosol particles or precipitation. Therefore, before 1900 UTC, we see small clouds were present, which were precipitating. During the early night, there were low levels of turbulence associated with clear skies and a stable boundary layer with a cold pool, but after 26 h we see an increase in turbulence that is associated with the appearance of a layer of low cloud. At the same time, the cold pool rapidly eroded (within 1 h), and a near-adiabatic temperature lapse rate became established (not shown) in a similar manner to the data presented in Fig. 12. The increased levels of turbulence under nocturnal stratocumulus cloud layers compared to nocturnal clear-air conditions appears to be a regular feature in the data. Various processes are likely to be responsible for the erosion of the cold pools under cloud, including advection, radiative heating from the cloud coupled with a ground heat flux, and increased levels of turbulence associated with the cloud. The relative importance of these processes remains to be established.

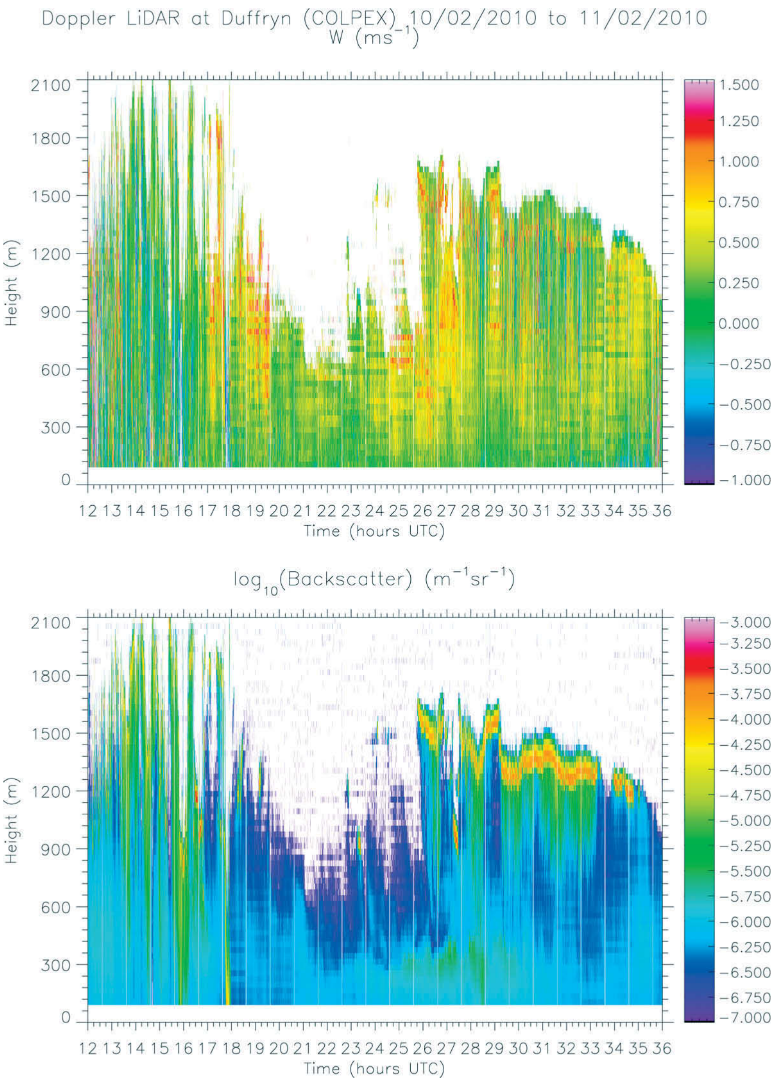

Fig. 13. Data from the Doppler lidar deployed at the Duffryn valley site. Times are hours after 0000 UTC 10 Feb.

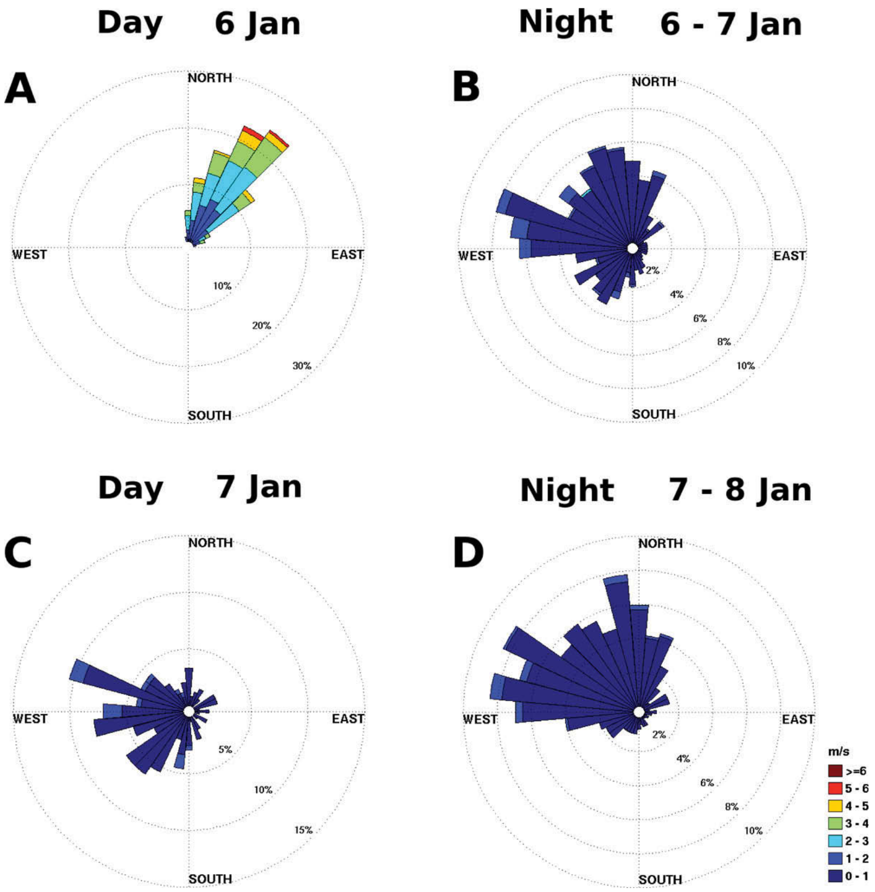

Fig. 14. Rose plots of wind speed and direction at Clun Castle from 6 to 8 Jan 2010 for the time periods (a) 1000–1400 UTC, (b) 2000–0800 UTC, (c) 1000–1400 UTC, and (d) 1800–0600 UTC.

Part of the weather station network included 10 automatic weather stations built and deployed by the University of Leeds (United Kingdom) (see Fig. 2 for locations). Figure 14 shows examples of measured wind speed and direction at Clun Castle for 6–8 January 2010. The temperature inversions and cold pools occurring during the nights for this period are evident in Fig. 12. For the daytime period on 6 January, the mean wind speed and direction were 2.4 m s^{-1} and 32° (northeasterly), respectively, with the latter being similar to the synoptic wind direction at the time and indicating that the valley was coupled to the boundary layer above. During the night of 6–7 January, winds became light (mean wind speed < 0.5 m s^{-1}) and the direction switched to a roughly down-valley gradient (297°), consistent with the development of a drainage flow (the synoptic wind direction measured at Springhill remained northeasterly). However, note the large variation in wind direction and that, at times, the wind flows up the valley. This result has been seen at several of the other valley sites and seems to be typical for measurements on stable nights, indicating that drainage flows are generally light and superposed on a wind field with significant fluctuations.

Another interesting feature from these results is the contrast between characteristics of wind speed and direction for the two daytime periods. During the daytime period on 7 January, winds remain light (less than 0.5 m s^{-1}) and significantly backed (about 259°) compared to the synoptic wind direction (325°; deduced approximately from the 30-m measurements at Springhill), which is similar to the previous nighttime period. Figure 12 shows that the cold pool did erode for this period, but it seems likely that the momentum fluxes (unfortunately not measured in the valley on this day) were insufficient to establish a synoptic wind direction within the valley. This in part may be due to the significant snow cover during the period, which (due to its albedo) would have reduced heat and momentum fluxes. The persistence of the westerly wind component at Clun Castle during the daytime period on 7 January may have been caused by channeling of flow along the valley axis by the synoptic winds above, as outlined by Whiteman and Doran (1993). Such effects complicate the analysis, so that at present it is uncertain whether the down-valley winds seen on the night of 7–8 January resulted from drainage flow or wind channeling. Further investigation is needed to clarify this.

COLPEX MODELING. COLPEX plans include a hierarchy of modeling activities aimed at improving understanding and enabling prediction of the local flow given accurate knowledge of the larger-scale flow. Scientific analysis will be based on best estimates of the larger scale.

Much of the modeling will use the Met Office Unified Model (MetUM). This model solves nonhydrostatic, deep-atmosphere dynamics using a semi-implicit, semi-Lagrangian numerical scheme (Cullen et al. 1997; Davies et al. 2005). The model runs on a rotated latitude–longitude horizontal grid with Arakawa C staggering and a terrain-following hybrid-height vertical coordinate with Charney–Phillips staggering (Davies et al. 2005). It includes a comprehensive set of parameterizations, including surface (Essery et al. 2001); boundary layer (Lock et al. 2000); mixed phase cloud microphysics (Wilson and Ballard 1999; enhanced to optionally include up to five condensed phase classes); and convection (Gregory and Rowntree 1990; with additional downdraft and momentum transport parameterizations), though the convection scheme is not used in models with horizontal resolutions of 1.5 km and higher.

The initial focus of the modeling will be on the IOPs. These will be used to develop and validate the model configuration. An initial configuration has been set up and tested using a nested suite of model domains: the innermost of which has a horizontal resolution of 100 m, with a size of 30 km × 30 km centered on the COLPEX sites (see Fig. 1; therefore larger than the area displayed in Fig. 2). In order to minimize lateral boundary effects, the variable horizontal resolution capability of the MetUM has been used to enlarge this domain to approximately 80 km × 80 km, by smoothly decreasing the resolution outside the regularly spaced central region toward 1.5 km at the boundaries. The grid spacing increases at a rate of approximately 5.5% per grid box within this stretching zone. The model uses source orography data with 100-m-resolution and 25-m-resolution land-use data (Fuller et al. 1994).

Lateral boundary data for the innermost grid are taken from a 1.5-km-resolution domain, using data that are updated every 10 min. The boundary conditions are applied using "Davies relaxation" (Davies 1976). The 1.5-km-resolution grid covers the southern half of the United Kingdom and is itself located within the Met Office operational 4-km-resolution mesoscale domain, which contains the whole of the United Kingdom. For the validation runs, the objective is to drive the larger scales in the model with data as close to reality as possible. Therefore, the 1.5-km model uses lateral boundary and initial conditions from each 3-h cycle of the operational 4-km-resolution 3D variational data assimilation (3DVAR) analysis system, whereas the inner 100-m-resolution model runs freely (i.e., it is not reinitialized every 3 h) and is driven only by the lateral boundary conditions. The intention is that the analysis tightly constrains the innermost domain but that this domain can freely evolve at the finest scales. The additional COLPEX data have not been used in the operational analysis or data assimilation so as to provide an independent test of the model.

In the innermost (100-m resolution) domain, the standard 1D boundary layer scheme is replaced with a 3D stability-dependent Smagorinsky–Lilly scheme. The same vertical grid is used in all three domains. The model upper boundary is placed at 40-km altitude, and the grid consists of 70 levels. The vertical grid spacing increases quadratically with height, with 10 levels below 500 m. The lowest two model levels (on which potential temperature is stored) are 5 and 21.7 m above the ground. Higher vertical resolution will be investigated in the near future, along with the dependence of results on the subgrid turbulence closure. It is well known that model predictions can be sensitive to such details even at the very fine resolutions of a few meters typically used in large-eddy simulations (e.g., Beare et al. 2006; Burkholder et al. 2010).

The horizontal resolution of the Met Office's highest-resolution operational forecast model is now 1.5 km and is likely to remain around 1–1.5 km for a number of years. The impact of small-scale orography still needs both parameterizing within the model and adjusting for in forecast products using postprocessing techniques. The intention is to run a validated version of the high-resolution (100 m) model for long time periods (e.g., several months of the experimental period) to provide a reference dataset to compare with data from the 1.5-km-resolution model together with evaluation of various postprocessing techniques. It will also be used to develop consistent fields of slowly varying prognostics (soil moisture and soil temperature) both for comparison with observations and to facilitate case studies aimed at studying sensitivity to model physics and resolution.

Initial model results. An example of a preliminary run of the MetUM for the 9–10 September case study can be seen in Fig. 15 (showing screen temperature). Data from the three main sites and the HOBO stations are overplotted for comparison. The plot shows the model has simulated cold pools of air in the valleys as expected (green and blue colors), with warmer air (yellows and oranges) on the higher ground. Comparison shows the simulated temperatures are generally within about 2°C of the observed temperatures, although there are some locations showing greater deviation. In both the Duffryn and Burfield valleys, the model cold pool appears generally a little cooler and more widespread than the observations indicate. Further comparisons may reveal systematic differences. Unfortunately, the HOBO measurement at Clun Castle was not available for this day. Close examination of the device revealed a chewed cable. Despite a protective fence around the device, footprints revealed that the likely culprit was a small calf that had managed to squeeze through!

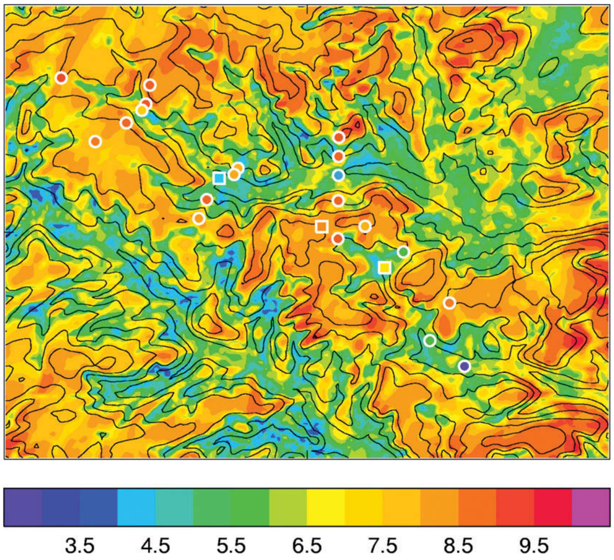

Fig. 15. MetUM screen level temperature from the 100-m-resolution run (initialized at 1600 UTC 9 Sep) at 0400 UTC 10 Sep 2009. Presented data are a 10-min average. Overplotted squares are screen temperatures from the three main sites, and circles are temperatures from the HOBO stations. Black lines are topographic contours. The area and orientation depicted are identical to Fig. 2.

SUMMARY AND DISCUSSION. The COLPEX field study was conducted in a region of small hills typical for the United Kingdom, over a period of 15 months. Three main stations and 30 smaller ones were deployed in a network approximately 15 km × 10 km in size. The principal aim was to study cold pooling of air in the valleys on stable nights. A total of 17 intensive observation periods were conducted to study some of the cold pools in detail. Initial results indicate that cold pooling of air in the valleys is relatively common and that the lowest temperatures in these conditions are found at the lowest valley elevations. It is notable that these cold pools remain strongly statically stable at all times. This stability will act to resist any drainage flow into and down the valley. Also, because turbulence will act to erode this stability, it is clear that radiative processes dominated in these boundary layers. Data from the analysis so far indicate a situation where any slow local drainage flows must have been forced and modulated tightly by the radiative heat balance and were in close equilibrium with it and the strong static stability. The light winds observed showed significant variation in direction and at times were seen to flow up the valley. There is no evidence to support the notion of negatively buoyant gravity currents "pouring" down the valleys, which would act to establish an adiabatic temperature profile. The observations indicate that any flow into and down the valley must have been slow enough such that its diabatic cooling rate and buoyancy was consistent with the evolution of static stability within the valley.

Results have shown that on a particular night the minimum temperatures in cold pools can be different in different valleys and that some valleys are systematically colder than others are during these periods. Furthermore, observations on the ridge-top site indicated that only weak and shallow stable boundary layers are present there. The results have indicated greater turbulence here than in the valley, and this is likely responsible for some of the observed structure. In addition, it is also possible that the shallow nature of the boundary layer there is partly caused by the slow drainage flow from the hilltop into the valley described above, preventing deep stable boundary layer formation on the high ground. However, further investigation is required to confirm this. Because the Burfield valley is more open and appears less sheltered than the Duffryn valley, the generally warmer temperatures and greater turbulence seen there during cold-pool episodes is evidence to support the notion that sheltering of valleys by hills is a significant effect in determining cold-pool formation and evolution. Initial results have also indicated some of the complexity of cold-pool evolution, such as the rapid erosion of stability observed when cloud advects over an area and the subsequent reformation of a cold pool when skies become clear again.

The observations made during COLPEX form an important dataset for numerical models to simulate. Initial high-resolution (100 m) modeling studies have successfully simulated cold-pool structure within the valley system. The distribution of temperature within the different valleys appears plausible, though, for the run presented, some of the cold pools appear slightly too cold. It is expected that the COLPEX dataset will move us a long way toward our goals to better understand the formation of cold pools and the distribution of nighttime temperatures in regions of small hills.

ACKNOWLEDGMENTS. The COLPEX experiment is indebted to many contributors. In particular, we wish to thank Dave Bamber, Tony Jones, Robert Clark, Martyn Pickering, Simon Osborn, Adrian Lock, Helen Wells, Stuart Webster, Jonathan Wilkinson, Matt Hobby, Matthew Gascoyne, and Mark Bart, who were all involved in the data collection campaign. The generosity of all the landowners who allowed free access to their land to host our network of weather stations is gratefully acknowledged. The support of the National Centre for Atmospheric Science (NCAS) is also acknowledged.

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A WEATHER AND CLIMATE ENTERPRISE STRATEGIC IMPLEMENTATION PLAN FOR GENERATING AND COMMUNICATING FORECAST UNCERTAINTY INFORMATION

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The AMS Board on Enterprise Communication set goals and prepared a road map of tasks for enterprise sectors—led by the National Weather Service—to work on together to make uncertainty information integral to hydrometeorological forecasts.

Imagine it is a July afternoon and you are scheduled to take a flight from Washington, D.C., to Cleveland. You check in, go through security, and then head to your gate where a signboard says your flight is "on time." Meanwhile, thunderstorms start to develop along the middle of your route. In response, air traffic controllers try to reroute planes. A ground halt is declared for other planes preparing to fly through the thunderstorm zone. Delays develop, and the plane that you would have boarded is rerouted and becomes late. When it finally arrives at Ronald Reagan Washington National Airport (DCA), it is determined that the crew will exceed its legal flight length maximum if the flight to Cleveland goes forward. With no other crew immediately available, your flight is canceled. You try to rebook, all the while thinking there has to be a way of avoiding such cancellations. There is such a way being planned for the next generation of air travel, and it involves the use of weather forecast uncertainty information to

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

DOI:10.1175/BAMS-D-10-00073.1

In final form 21 July 2011

anticipate future delays and minimize their impact (see sidebar and FAA 2011).

A great success of twentieth-century science and technology was developing the ability to forecast future weather conditions. The skill and accuracy of these forecasts have increased enough to improve decisions protecting life and property; health; national defense and homeland security; and socioeconomic, ecosystem, and individual well-being. Beyond the 1–2-week "weather regime," much progress has also been made in predicting expected conditions (e.g., above or below normal temperature, precipitation, drought, and storminess) associated with seasonal to interannual climate variability (e.g., El Niño) and even longer-term, scenario-based climate change. However, despite these successes, weather, water, and climate (hydrometeorological) forecasts are far from perfect. Errors in forecasts adversely affect not only decisions and outcomes but also decision makers' confidence in using the forecast information in the first place.

Forecast uncertainty depends on many factors. Generally, it increases as the forecast lead time (referred to here as forecast lead) increases. Forecast uncertainty also increases more quickly for smaller-scale (size and duration) phenomena, such as tornadoes and thunderstorms, than for larger-scale phenomena, such as a winter storm (Fig. 1). Additionally, forecast uncertainty grows more quickly in dynamically

EXAMPLES OF THE USE AND BENEFITS OF FORECAST UNCERTAINTY INFORMATION

Currently, weather impacts are associated with 70% of all air traffic delays within the National Airspace System, amounting to a cost of ~$28 billion per year, and about two-thirds of these delays could be avoided with better weather information (Abelman et al. 2009). These delays and costs are projected to escalate over the next 15 years as air traffic demand doubles or triples by 2025 (NRC 2008). A key goal of the Federal Aviation Administration's (FAA) Next Generation Air Transportation System (NextGen) is to reduce these delays by improving weather information and the use of weather information in air traffic management decision making (FAA 2011). Documented NextGen requirements (JPDO 2007) for improved weather information already include probabilistic weather forecasts. A study by Keith and Leyton (2007) showed that one airline alone could potentially save $50 million annually on domestic flights by relying on probabilistic terminal weather forecasts to save fuel and other associated costs. Another study (Steiner et al. 2008) showed how en-route weather probability information can be translated into anticipated airspace capacity reductions and consequently into shorter delay times and substantial cost savings, by enabling aircraft to fly shorter routes around weather hazards.

The military needs forecast uncertainty information to identify, assess, and mitigate risk resulting from hydrometeorological hazards during military operations. For example, atmospheric and oceanic hazards (e.g., strong winds and high seas) pose risks for ships at sea, and flood and high-water hazards impact ground-based operations. Forecast probabilities (obtained by using ensemble prediction systems and/or other techniques) of these and other hazards exceeding certain thresholds (with escalating impact on the mission) can be used in so-called Operational Risk Management (ORM) tools (OPNNAV 2010). The U.S. Navy is developing one such capability employing ORM to translate objective weather uncertainty guidance directly to piracy risk. In particular, the U.S. Department of Transportation Maritime Administration estimates that piracy around the Horn of Africa costs the U.S. maritime industry between $1 billion and $16 billion per year (Chalk 2009). Pirates operate in small vessels and therefore are particularly vulnerable to adverse wind and seas. The hypothesis is that pirate activity will likely be lower in areas of high meteorological risk compared to low risk. The Fleet Numerical Meteorology and Oceanography Center ensemble forecasts are used to identify the probability of various thresholds of surface winds and seas, enabling an assessment of piracy risk. Knowledge of the risk that pirates will assume by operating in a particular region at a particular time can be exploited to protect shipping through various forms of interdiction and avoidance efforts. In the example shown in Fig. S1, the meteorological risk to pirates operating in the Mogadishu area is much smaller than near the Gulf of Aden area at hour 84 (the pattern of risk changes with forecast lead). Therefore, based on this risk, pirate activity would be expected to be higher in the Mogadishu area. With this tool based on multivariate meteorological forecast uncertainty information, decision makers can take action, for example, by moving naval assets to areas that are favorable for piracy activity, providing divert recommendations to shipping, or other means.

The energy sector is one of the most weather- and climate-sensitive sectors of the economy, and a near-term challenge is establishing the smart energy grid. The current grid limitations and vulnerability to failure are reported to cost the nation $80 billion–$188 billion per year in losses due to power outages and power quality issues (Repower America 2010). To improve energy production and management, a probabilistic integrated renewable energy resource forecast of variability and thresholds, such as accumulated precipitation, wind, and solar radiance, could be utilized. The transformation of probabilistic climate forecasts into probabilistic energy demand, production, and operational risk scenarios is a high priority for predicting electricity consumption and peak load.

Probabilistic hydrometeorological forecasts could also be used to increase active regions around storms than in the middle of quiescent, fair-weather regimes. Typically by two weeks, uncertainty is large enough that forecast skill (predictability) is lost for nearly all types of weather (Simmons 2006; Tribbia and Baumhefner 2004) and the predictability/uncertainty of climate-scale anomalies becomes the question.

Uncertainties in hydrometeorological forecasts can be reduced through improved observations, data assimilation, and numerical modeling techniques. However, forecast uncertainty can never be completely eliminated no matter how much science and technology are applied to the problem because the atmosphere, oceans, and related Earth systems are inherently chaotic. According to chaos theory (Lorenz 1963), popularly known as the "butterfly effect," nearly perfect routine forecasts can never be achieved because of the exponential growth of unavoidable very small errors (perturbations) in forecast model initial conditions.

Despite a growing theoretical understanding of forecast uncertainty and an increasing ability to quantify it with ensemble prediction techniques, "deterministic" forecasting is still standard for most hydrometeorological applications. As the name implies, the goal of deterministic forecasting is to determine and communicate a single, most accurate value for a future hydrometeorological element, such as tomor-

business productivity and competitiveness as well as enhance public well-being, especially with respect to public health. For example, it has been estimated that in the United States poor air quality causes as many as 60,000 premature deaths each year, and the cost associated with air pollution–related illness alone ranges from $100 billion to $150 billion per year (NOAA 2010). Probabilistic forecasts could provide earlier notice about the risk for poor air quality to individuals and communities and help them limit exposure and reduce asthma attacks; eye, nose, and throat irritation; and other respiratory and cardiovascular problems and therefore save lives. Although it is difficult to estimate how many lives and costs could be saved with accurate and reliable air quality predictions, assuming that such predictions reduce by 1% the premature deaths and the costs listed above, about 600 lives and more than $1 billion (NOAA 2009) could be saved each year.

Two other examples that could benefit from probabilistic information are ocean-state and ecosystem forecasts.[1] A forecast of the ocean state would include probabilistic sea surface temperature forecasts but also, as the need arises, probabilistic forecasts of elements such as oil concentration. The spring 2010 Deepwater Horizon oil spill in the Gulf of Mexico provided a general illustration of the difficulties in quantifying uncertainty as well as the potential benefits. Uncertainty estimates for the amount of oil leaking changed dramatically in the weeks and months after the spill. A more precise quantification of the uncertainty of oil flows from the wellhead may have changed the actions of both governmental and industrial officials. During future oil spills, ensemble prediction techniques applied to the ocean would provide a range of estimates of oil concentrations and how they would evolve with time. These oil concentration estimates could then be used as inputs to models of affected ecosystems (e.g., along the Gulf Coast), yielding probabilistic estimates of the range of impacts. This impact information could be used to prioritize and appropriately target cleanup resources and marshal solutions more quickly. For example, perhaps resources would be targeted to the most vulnerable ecosystems at highest risk.

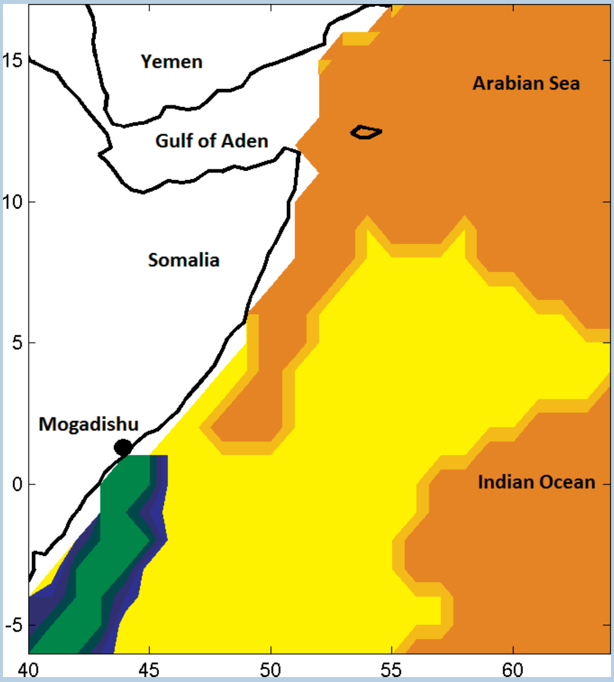

Fig. S1. Example 84-h forecast of the meteorological risk to pirates operating around the Horn of Africa (i.e., the risk to pirates operating in an area due to meteorological conditions) scaled from high risk (orange) to low risk (green).

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[1] Here, ecosystem forecasts refer to the prediction of the impacts of physical, chemical, biological, and human-induced change on ecosystems and their components (Valette-Silver and Scavia 2003).

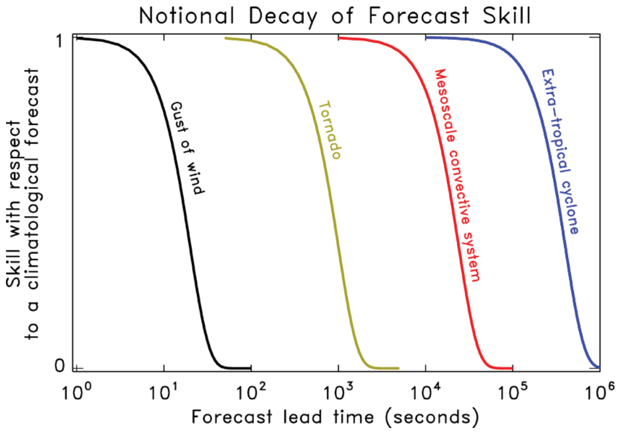

Fig. 1. Notional decay of forecast skill (0 is no skill compared to climatology and 1 is perfect skill, i.e., agrees perfectly with observations) as a function of lead time in seconds. Theoretically, a perfect forecast can be produced with a perfect model and perfect initial conditions. However, the initial state cannot be known perfectly and even exceedingly small errors will grow rapidly during the forecast, eventually making even a perfect-model ensemble forecast no more skillful than a climatological forecast. The time scale when zero skill is reached generally depends on the scale of the phenomenon. This time scale is determined by the phenomenon, not the model. For most of these phenomena, the skill of current forecasts decreases much more rapidly than these curves with a perfect model and may end up below zero because of model imperfections.

row's high temperature. Although there are notable exceptions, such as hurricane track, wind and storm surge forecasts, and precipitation forecasts, most current operational forecast products and services are based on single-value predictions with little or no accompanying forecast error or uncertainty information. In part, deterministic forecasts likely have been the format of choice because the public desires easy-to-understand, unambiguous predictions. In some cases, communication time and format restrictions have also played a significant role in the choice of presentation formats. For example, broadcasters may only have minutes or even seconds to deliver a weather forecast and have no time to explain vagaries in the forecast. Moreover, determining what forecast uncertainty information users actually need and can benefit from and how to communicate the information (e.g., forecaster confidence, alternate scenarios, probabilities) effectively is a challenging task requiring the application of social, behavioral, and economic science, outreach, and education. Nevertheless, the consequence of conveying only single-value information is that poorer decisions may be made by users because they do not have the benefit of knowing and accounting for the forecast uncertainties and risks upon which their decisions are based.

After reviewing the societal needs and potential benefits of forecast uncertainty information, the National Research Council (NRC; NRC 2006) and the American Meteorological Society (AMS; AMS 2008) conclude that there are compelling reasons for the U.S. weather, water, and climate enterprise (referred to here as the Enterprise) to consider uncertainty as an integral and essential component of all hydrometeorological forecasts. These reports recommend that quantifying and communicating forecast uncertainty based on the probability of possible outcomes should be emphasized in addition to the current practice of determining and communicating the single most probable forecast.

In response to these and other studies and reports recognizing the scientific, socioeconomic, and ethical value of quantifying and effectively communicating forecast uncertainty information, the AMS Commission on the Weather and Climate Enterprise (CWCE) Board on Enterprise Communication commissioned the Ad Hoc Committee on Uncertainty in Forecasts (ACUF) to formulate a cross-Enterprise plan to provide forecast uncertainty information to the nation. The resulting Weather and Climate Enterprise Strategic Implementation Plan for Generating and Communicating Forecast Uncertainty (Hirschberg and Abrams 2011; referred to here as the Plan) is now available on the AMS website (at www.ametsoc.org/boardpges/cwce/docs/BEC/ACUF/2011-02-20-ACUF-Final-Report.pdf) and is summarized here.

The Plan defines a vision, strategic goals, roles and responsibilities, and an implementation road map that will guide the Enterprise toward routinely providing the nation with comprehensive, skillful, reliable, sharp, and useful information about the uncertainty of hydrometeorological forecasts. As an overview of the use and benefits of forecast uncertainty information, the Plan offers several scenarios of how hydrometeorological forecast uncertainty information can improve decisions and outcomes in various socioeconomic areas (see sidebar). For example, shifting to a warning capability, which incorporates probabilistic forecasts and thresholds into the warning criteria, a "warn on forecast" (WOF; Stensrud et al. 2009) or "warn on probability" (WOP) capability could increase warning lead times[1] (see Fig. 2) and

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[1] Any new warning capability based on probabilities will need to be developed in conjunction with social science research to elicit needs for content, format, and channels of communication.

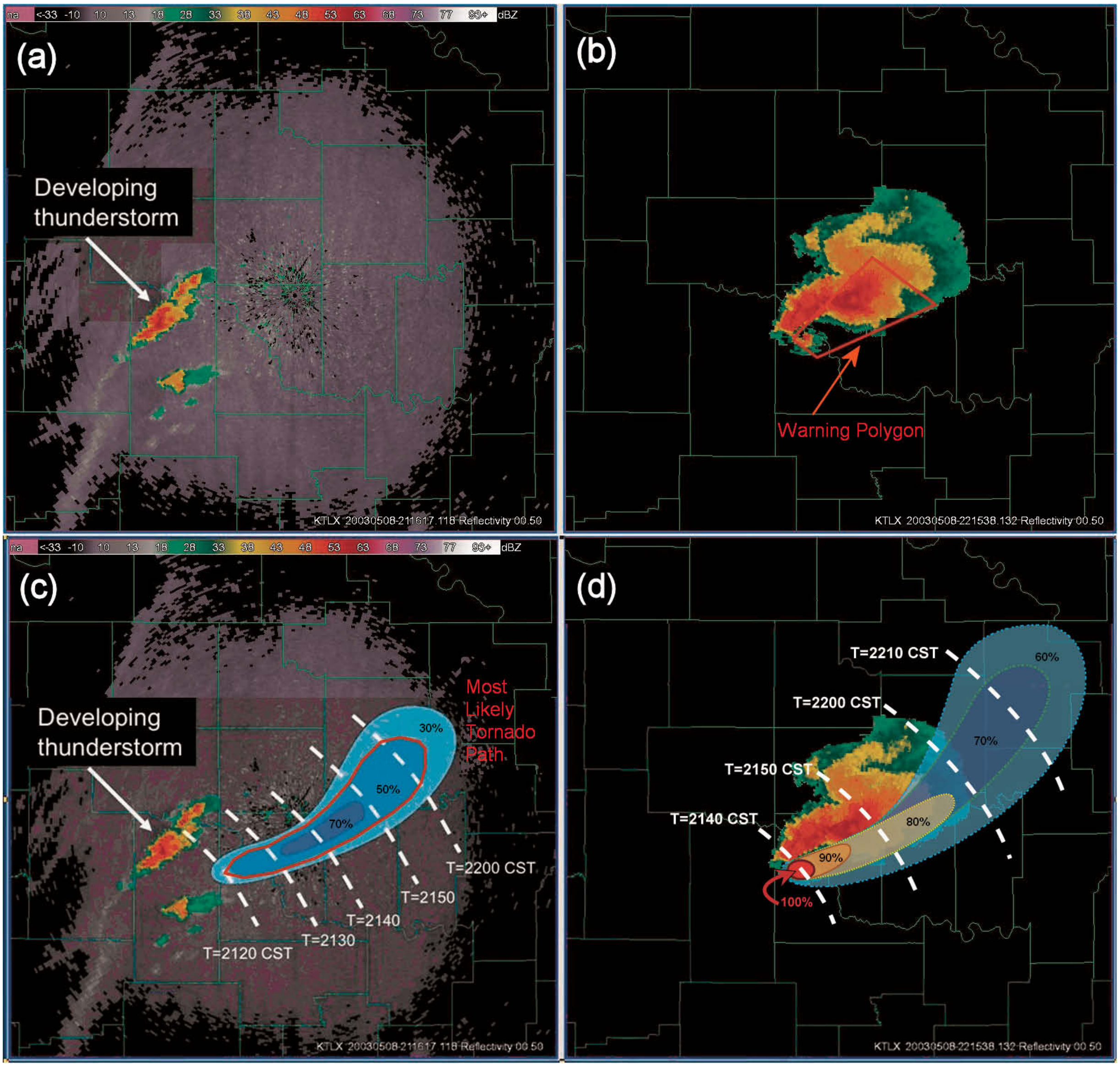

Fig. 2. Comparison of a tornadic thunderstorm evolution and the issuance of tornado warnings under the currently operational warn on detection (WOD) paradigm and a hypothetical warning application under a WOF or WOP paradigm. (a) Radar reflectivity of a developing thunderstorm. The radar reflectivity does not yet indicate the presence or formation of a tornado. (b) Radar reflectivity of the same thunderstorm after it has developed a mature mesocyclone radar signature (hook echo); a warning polygon (red box) indicates the geographic area under a tornado warning. Under the WOD paradigm, the warning polygon can only be issued when a mesocyclone signature [such as indicated in (b)] is detected by the radar or there is an actual observation (e.g., by a trained spotter indicating the formation of a tornado). (c) As in (a), but with a conceptual 1-h lead time probabilistic tornado path superimposed. (d) As in (b), but with an updated conceptual 1-h probabilistic tornado path instead of a warning polygon. Under a WOF/WOP paradigm, a tornado warning using appropriate probabilistic thresholds may be able to be issued when thunderstorms are in their incipient stages [as in (a)], providing more lead time. Adapted from Stensrud et al. (2009).

provide emergency managers, other decision makers, and the public additional valuable information by which to save lives and property.

The Plan is intended for a wide audience, including senior decision makers, program managers, service providers, and physical and social scientists. It is based on and is intended to provide a foundation for implementing recent recommendations in NRC (2006), AMS (2008), WMO (2008), and others, and it leverages emerging results from scientific and socioeconomic studies and the best practices of hydrometeorological services and industry from around the world.

VISION, STRATEGIC GOALS, AND IMPLEMENTATION ROAD MAP.

The vision described in the Plan is of a future where societal benefits of forecast uncertainty information are fully realized, a vision in which the use of forecast uncertainty information in decision making helps to

- protect lives and property;
- improve national airspace, marine, and surface transportation efficiency;
- strengthen national defense and homeland security;
- improve water resources management;
- sustain ecosystem health;
- improve energy production, safety, and management;
- increase business and agricultural productivity and competitiveness;
- provide a basis for sound, risk-informed planning; and
- enhance public well-being.

In order to reach this vision, the Plan defines four interrelated strategic goals and supporting objectives (Table 1) to meet the scientific and cultural challenges associated with a greater focus on probabilistic forecasts. Summary discussions of these strategic goals and objectives are presented later in this section. In the full version of the Plan, each objective has tabulated background information; the need for the objective; current capabilities and gaps; performance measures and targets; a proposed solution strategy; and specific tasks (with suggested Enterprise partner leads) that must be accomplished to meet the objective.

The Enterprise consists of four primary sectors: 1) the government sector, which includes local, state, and federal governments; 2) America's weather and climate industry, which includes consulting/service companies and media; 3) academia, which includes associated research institutions; and 4) nongovernment organizations (NGOs), which includes organizations like the AMS and National Weather Association. In order for the Plan to be successful, the Enterprise will need to leverage the expertise and resources of each sector to mainstream quantitative forecast uncertainty information (by using, e.g., probabilistic forecasts) into decision making. Increasingly, the missions, strengths, and capabilities among these sectors can overlap, making distinct delineations difficult. Nevertheless, there are leadership roles each partner group needs to fill to generate and communicate comprehensive forecast uncertainty information that can be used effectively by all decision makers, from the public and emergency management to agencies and corporations.

Strategic goal 1. Understand forecast uncertainty. Strategic goal 1 is to understand the hydrometeorological forecast uncertainty needs of society, including how humans can most effectively interpret and apply uncertainty information in their decision making; the natural predictability of the coupled atmosphere, oceans, and related Earth systems; and the optimal design of ensemble prediction systems. Meeting this goal will increase the Enterprise's understanding and knowledge about hydrometeorological forecast uncertainty, so that the Enterprise can communicate this information more effectively to users (strategic goal 2) and improve operational probabilistic prediction systems (strategic goal 3). First, understanding in several areas (objective 1.1) is needed to determine and provide uncertainty information that is most beneficial and to effectively communicate and assist users in using the information in their decision making under strategic goal 2. These areas include understanding how various types of users currently perceive, synthesize, and use uncertainty information to make decisions; how uncertainty information combines with other factors to influence decision making; what types of uncertainty information are needed; how needs for uncertainty information vary by hydrometeorological event; what formats will most effectively improve decision making; and how the needs for content and format vary by communication channel. At best, if this need is not met, the forecast uncertainty information the Enterprise provides will continue to go largely unused. At worst, uncertainty information will be misinterpreted or misused, leading to poor decisions and negative outcomes. A few preliminary studies exist on effective ways for communicating probabilistic information (Kuhlman et al. 2009). However, there is limited knowledge specific to the effective communication of hydrometeorological forecast uncertainty and risk to various customer and user groups. Although communicating uncertainty and risk has been studied in other fields and contexts, it is not apparent how this knowledge applies to communicating hydrometeorological forecast uncertainty.

Second, to improve operational probabilistic prediction systems (which produce the uncertainty information), an increased understanding of the nature of atmospheric predictability is needed (objective 1.2) to set reasonable forecast accuracy and reliability goals and to help prioritize the development of forecast uncertainty products and services. A more complete understanding of predictability will also provide insights about forecast model errors and help assess and improve data assimilation and other techniques to quantify forecast uncertainty. Although some rough quantification exists (e.g., predictability usually increases with the scale of motion), knowledge about the predictability of specific phenomena is lacking. For example, is a 3-day tornado outlook at the county scale more or less predictable than a 10-day hurricane track and intensity forecast? Current understanding does not allow quantification of the relative gap between the ability to forecast a phenomenon and the phenomenon's intrinsic predictability. Quantifying how this gap changes for various phenomena may help determine which aspects of forecast models are in greatest need of improvement.

TABLE 1. Strategic goals and supporting objectives.

Strategic goal 1 **Understand forecast uncertainty**	**Strategic goal 2** **Communicate forecast uncertainty information effectively, and collaborate with users to assist them in interpreting and applying the information in their decision making**	**Strategic goal 3** **Generate forecast uncertainty data, products, services, and information**	**Strategic goal 4** **Enable forecast uncertainty research, development, operations, and communications with supporting infrastructure**
Objective 1.1: Identify societal needs and best methods for communicating forecast uncertainty.	Objective 2.1: Reach out, inform, educate, and learn from users.	Objective 3.1: Improve the initialization of ensemble prediction systems.	Objective 4.1: Acquire necessary high-performance computing.
Objective 1.2: Understand and quantify predictability.	Objective 2.2: Prepare the next generation for using uncertainty forecasts through enhanced K–12 education.	Objective 3.2: Improve forecasts from operational ensemble prediction systems.	Objective 4.2: Establish a comprehensive archive.
Objective 1.3: Develop the theoretical basis for and optimal design of uncertainty prediction systems.	Objective 2.3: Revise undergraduate and graduate education to include uncertainty training.	Objective 3.3: Develop probabilistic nowcasting systems.	Objective 4.3: Ensure easy data access.
	Objective 2.4: Improve the presentation of government-supplied uncertainty forecast products and services.	Objective 3.4: Improve statistical postprocessing techniques.	Objective 4.4: Establish forecast uncertainty test bed(s).
	Objective 2.5: Tailor data, products, services, and information for private-sector customers.	Objective 3.5: Develop nonstatistical postprocessing techniques.	Objective 4.5: Work with users to define their infrastructure needs.
	Objective 2.6: Develop and provide decision-support tools and services.	Objective 3.6: Develop probabilistic forecast preparation and management systems.	
		Objective 3.7: Train forecasters.	
		Objective 3.8: Develop probabilistic verification systems.	
		Objective 3.9: Include digital probabilistic forecasts in the weather information database.	

Third, a fuller understanding of the sources of forecast uncertainty as well as efficient numerical methods for estimating uncertainty in prediction systems (objective 1.3) are also needed. The two primary contributions to uncertainty in a forecast are uncertainty in the model initial conditions and forecast model error (i.e., model uncertainty). Progress in understanding and estimating the former source of uncertainty is relatively more mature than the latter. Ensemble Kalman filtering and other optimal estimation techniques are being developed to improve initial condition uncertainty estimates and ensemble initialization. Ongoing challenges include improvement of analysis uncertainty estimates, especially for nonnormally distributed variables such as cloud liquid water. In comparison, efforts to better understand and develop techniques to quantify model uncertainty are only in their relative infancy. Although some model errors can be reduced through the regular model development process (i.e., improving model dynamics and traditional parameterizations, increasing resolution, etc.), there will always be errors associated with hydrometeorological processes occurring below the resolution (the "grid scale") of the model. For example, the common assumption in meteorological models has been that the effects of subgrid-scale processes could be "parameterized." That is, given the grid-scale conditions, the average effects of subgrid-scale motions could be estimated deterministically (i.e., every time grid-scale condition X occurs, the feedback from subgrid-scale effects is exactly Y). As the grid resolution is refined, this deterministic assumption is increasingly invalid; a wider and wider range of subgrid-scale effects Y are all plausible given the same forcing X (Plant and Craig 2008). If a range of effects Y is plausible but a single Y is consistently used, this may contribute to a lack of spread in ensemble forecasts. The implication for ensemble prediction is the need to better understand the random (stochastic) nature of parameterized hydrometeorological processes in models and to reformulate them to be stochastic.

Strategic goal 2. Communicate and collaborate with users. Strategic goal 2 is to communicate forecast uncertainty information effectively and collaborate with users to assist them in interpreting and applying the information in their decision making. Simply generating forecast uncertainty information (strategic goal 3) is not enough. Users must see the value of the information, collaborate with developers to determine what information is needed, and learn to use the information to help them make decisions. Objectives supporting strategic goal 2 apply existing and emerging understanding from the research community under strategic goal 1 to reach out to, educate, and work with users about uncertainty information and probability; sensitize and educate students (including hydrometeorological students) about the underlying physical theory and social science aspects of uncertainty; improve the general presentation of forecast uncertainty information and tailor it for users based on social science and user feedback; and provide decision-support tools and services to help users interpret and apply forecast uncertainty information in their decision making.

Generations of hydrometeorological users and the general public have grown accustomed to single-value deterministic forecasts. Inaccurate weather forecasts are disparaged and often satirized. New information and products that include forecast uncertainty could be viewed as a hedge against poor science and forecasts, although some social scientists argue that acknowledging uncertainties and unknowns builds credibility (Morrow 2009). Perhaps the negative connotation associated with the terminology "forecast uncertainty" argues that it should be replaced with "forecast certainty" to help put the information and its use in a more positive light. Nevertheless, outreach, education, and public information campaigns are needed to inform users and the public that forecast uncertainty is an inherent component of hydrometeorological prediction, and that comprehending and using uncertainty information can improve their decision making (objective 2.1). Moreover, users will also need ongoing collaboration with the hydrometeorological and social science community to determine what data and products they want and need and the proper format for optimal use.

More exposure to the basic concepts of probability and statistics in K–12 (especially with salient weather examples) will help children grow into adults who are more sensitized about uncertainty and the advantage of probabilistic forecasts and more likely to use the information in their decision making. Currently, the topic of uncertainty and use of probabilities in weather information only arises if math students happen to be given a probability example that has to do with weather. A more structured, systematic, and reinforcing approach is needed (objective 2.2) to illustrate and embed the concepts of probability and statistics in hydrometeorology in our nation's youth.

Undergraduate and graduate students in hydrometeorological science need a better basic understanding of chaos theory, the fundamentals of ensemble predication, probabilistic forecasting, and the use of uncertainty guidance for decision making. They also need a broad understanding of the social sciences and effective communication techniques (objective 2.3).

Improving the effectiveness of the day-to-day communication of forecast uncertainty information will involve both improving the presentation (e.g., formats) of government-supplied uncertainty forecast products and services (objective 2.4) and tailoring uncertainty information by the commercial sector for specific customers (objective 2.5). Many, if not most, users of forecast uncertainty information will not encounter it in a purely digital form from such sources as a weather information database (see objective 3.9) but rather through regularly available products. By leveraging social science research results and user feedback (see objectives 1.1, 2.1, and 4.4), these products will need to be formatted to best convey the breadth of uncertainty information iconically, graphically, textually, and/or numerically (e.g., Joslyn et al. 2009). Although there are no established Enterprise standards for graphical uncertainty products, there are examples of ways of displaying data (Fig. 3). NRC (2006) and WMO (2008) also provide some ideas about how probabilistic information could be conveyed effectively and are good starting points for the complex process of designing appealing and useful new web pages and web services for uncertainty products.

Finally, decision-support tools and services are needed (objective 2.6) to link forecast uncertainty information and direct user impacts and risk tolerance. Single-value deterministic forecasts severely limit the utility of weather, water, and climate forecast information because they do not allow users to apply probabilities to their own thresholds (i.e., risk assessment) when making decisions. In contrast, the multiple possible forecast outcomes produced by ensembles can support decisions of various levels of sophistication depending on a user's cost/loss considerations. Automated decision-support systems can ingest probabilistic forecasts into preset user threshold/risk tolerance algorithms that generate a recommended decision based on optimizing the cost/benefit. To be successful, the Enterprise will need to collaborate with users to understand their decision framework. In the end, many decisions are deterministic: go or no go, do it or do not do it. However, in some cases, the timing, venue, methodology, etc., may be changeable, perhaps depending on various hydrometeorological outcomes. All of these decisions could be helped if uncertainty information were presented in a way the decision maker could understand and use to her or his best advantage.

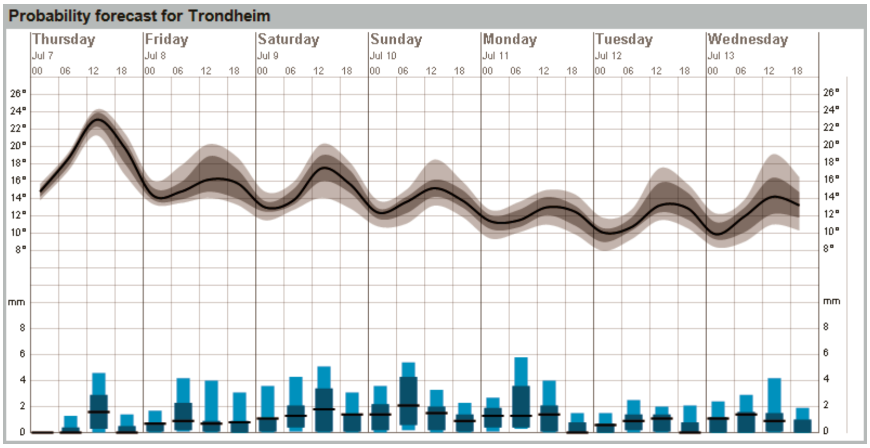

Fig. 3. A weather forecast graphic for Trondheim, Norway, indicating numerical probabilities for different possible temperature and precipitation occurrences as a function of time. (Image from www.yr.no, a website by the Norwegian Meteorological Institute and the Norwegian Broadcasting Corp.)

Strategic goal 3. Generate forecast uncertainty data, products, services, and information. Strategic goal 3 is to generate reliable, high-resolution weather, water, and climate probabilistic and other forecast uncertainty data, products, services, and information that meet users' emerging needs for uncertainty information. Currently, the National Weather Service (NWS), and other parallel organizations, such as the U.S. Navy and Air Force, operationally generate mostly deterministic hydrometeorological forecast data and information by employing the following forecast process:

- Collect observations.
- Apply data assimilation techniques to synthesize the observations together with prior forecasts to produce initial conditions for numerical prediction models.
- Run the models to produce numerical prediction forecasts.
- Postprocess the raw model output statistically and otherwise to reduce errors.
- Produce objective and human forecaster–modified guidance, forecast, and warning data and information.

For the most part, all of this forecast information is made available to Enterprise partners. The Enterprise partners, including the NWS and similar government operational organizations, in turn use this information as a foundation for generating products, services, and other value-added information that they communicate to their customers and users.

A key to meeting strategic goal 3 is to enhance and establish a similar capability to generate and make available routinely to Enterprise partners a "foundational" set of forecast uncertainty data and information for a range of variables and forecast leads, which the Enterprise partners can use to meet their mission and customer needs. For the most part, the routine generation of this foundational set of forecast uncertainty information should remain primarily the responsibility of the government sector because of the resources and infrastructure required to support this activity. However, all Enterprise partners will be communicating this information to their users and customers either in its raw form or through value-added products, services, and information.

It will be necessary to continue to collaborate with users, social scientists, and partners by using ongoing strategic goals 1 and 2 outcomes to define what this foundational forecast uncertainty dataset should be and how it will evolve. This dataset likely will include observation and analysis uncertainty information, raw and postprocessed ensemble model output, and human value–added information for forecast leads out to several weeks (see Table 2 for examples). Uncertainty information will be stored in ways both compact and informative; this may include the data to estimate the full probability density functions (PDFs).

Generating and making available this foundational set of forecast uncertainty data and information will require changes in the forecast process. The needed changes are reflected in the objectives listed under strategic goal 3 in Table 1. These objectives will leverage the new understanding about forecast uncertainty gained under strategic goal 1, and user and customer feedback that is part of strategic goal 2. Enhancements to information technology (IT) and other infrastructure improvements will also be

Table 2. A sample of the types of forecast uncertainty information that should be generated operationally and made freely available as part of a foundational set.

1) Continuous variables

- Temperature and dew point
  - ° Hourly, daytime maximum, and nighttime minimum temperatures mean and range of uncertainty (e.g., 10th/50th/90th percentile of forecast distribution)
  - ° Extreme temperature probability of exceedance
  - ° User-specific probability of exceedance (e.g., subfreezing thresholds for crop growers, materials applications thresholds for concrete pourers)
- Wind speed
  - ° Exceedance values for predefined thresholds (e.g., gale, hurricane force)
  - ° User-specific probability of exceedance (e.g., wind-energy industry)
- River level and flow
  - ° Exceedance values for predefined thresholds (e.g., minor, moderate, major flood stage)
  - ° Volume of water into reservoirs for optimal water management

2) Quasi-continuous variables

- Wind direction and wind gust PDFs (critical for aviation, wind energy industry, and temperature forecasts)
- Sky cover and cloud optical depth PDFs (critical for solar energy industry and aviation/transportation sector)
- Ceiling height PDFs (critical for aviation)
- Visibility PDFs (critical for aviation)
- Precipitation [probabilistic quantitative precipitation forecast (PQPF), timing, and precipitation type]
  - ° PQPF probability of exceedance values such as 0.1", 0.25", 0.5", 1", 2", etc., including flooding exceedance values
  - ° Probability of precipitation shortfalls (e.g., drought and water availability)
  - ° Precipitation timing (onset/cessation), including timing of any changeover in precipitation type (e.g., 60% chance of snow will arrive in Boulder between 4 and 6 pm, 20% chance between 2 and 4 pm, and 20% chance between 6 and 8 pm)

3) Discrete weather elements

- Severe weather

necessary to achieve these objectives; such supporting improvements are covered under strategic goal 4.

Objectives 3.1–3.9 focus on improving the steps by which forecasts are produced and uncertainty data and information are generated and made available to Enterprise partners. Note that, although the observations that are used to initialize the forecast process are also uncertain, no observation uncertainty objective is included here because it is judged that observation uncertainty is already handled adequately by instrument designers and data assimilation scientists.

New and improved data assimilation techniques are needed (objective 3.1) that can produce an ensemble of initial conditions that is accurate, can sample the range of possible true analyses, and can project upon growing forecast structures so that differences between member forecasts grow (appropriately) quickly. Existing techniques are typically designed to produce sets of initial conditions that primarily grow quickly but, in doing so, do not necessarily reflect flow-dependent analysis uncertainty accurately. As forecast spatial and temporal resolution increases, these techniques must be able to estimate uncertainty at the mesoscale as well as the synoptic and planetary scales.

Improved ensemble prediction methods (objective 3.2) are needed that can propagate the initial conditions forward in time and provide reasonably sharp and reliable probabilistic forecasts, correctly accounting for the uncertainty due to model error. Current-generation ensemble prediction systems produce uncertainty forecasts that are biased and underestimate the forecast uncertainty (i.e., underdispersion of the ensemble members collectively). This is partly because of the low resolution of the forecast models, partly because of improper initial conditions, and partly because the ensemble prediction systems do not include effective treatments for the error introduced by model deficiencies.

Often, the accuracy of the first few forecast hours of numerical weather prediction (NWP) model

Table 2. Continued.

  - ° Probability of tornado occurrence within 25 mi (40 km) of a point
  - ° Probability of extreme tornado
  - ° Probability of any severe weather (tornado, winds, and hail)
- Tropical cyclones
  - ° Probabilistic intensity values (e.g., 50% chance of category 1 at landfall)
  - ° Probabilistic storm surge values with inundation mapping of each probability
  - ° Probabilistic storm track (e.g., probabilistic information within "cone of uncertainty")
- Flooding
  - ° Probability of exceeding streamflow heights (e.g., location-specific levee heights, inundation mapping)
  - ° Probability of time until exceeding river heights and duration above threshold

4) Earth- and near-terrestrial-system elements

- Avalanche probability for a given area
- Mudslides/debris flows probability for a given area
- Tsunamis
- Space weather (e.g., solar storms)

5) Multivariable probabilities

- Heat index (e.g., combining temperature and dewpoint)
- Wind chill (e.g., combining temperature and wind speed)
- Fire weather [e.g., combining temperature, dewpoint, wind speeds, and probability of preceipitation (POP)]

6) Multiple weather and water climate scenarios

- Aviation applications (individual gridded scenarios from an ensemble input into flight-routing software)
- Hydrologic forecast chains on weather and climate time scales (individual time series of possible rainfall/temperature and other hydrologic forcing scenarios fed into ensemble of hydrologic forecast models to produce ensemble of streamflow estimates)
- Probabilistic drought outlooks

guidance, including ensemble guidance, is poor because the NWP models need several model hours to "spin up" (i.e., develop internally consistent vertical motions) (Roberts and Lean 2008). Because of this, new probabilistic nowcasting techniques (objective 3.3) are needed to generate reliable probabilistic forecast information for forecast leads of zero to several hours. Most current nowcasting techniques are deterministically based and have their roots in extrapolation techniques used on existing features, which may not properly account for stochastic aspects, especially new feature development or dissipation of existing features.

The need for statistical postprocessing (objective 3.4) of raw ensemble model output to ameliorate bias and other deficiencies will likely never be completely eliminated despite improvements in ensemble prediction methods (objectives 3.1 and 3.2). Additionally, statistical postprocessing can "downscale" (Cui et al. 2009) relatively coarse-resolution model output to finer detail and also be used to derive quantities not directly predicted by the model that may be required by users (Hamill et al. 2006). Most current statistical postprocessing techniques (e.g., model output statistics; Glahn and Lowry 1972) are based on deterministic model output. A variety of new ensemble model–based calibration techniques (e.g., ensemble kernel density model output statistics; Glahn et al. 2009) appear to perform relatively well for normally occurring weather and relatively short forecast leads. However, for rare events and long-lead forecasts, longer training datasets of "reforecasts" and new statistical techniques may be needed (Hamill et al. 2006); for example, in order to correct biases in the position of a hurricane in the Gulf of Mexico, observed and forecast tracks from many similar storms in the Gulf of Mexico will be needed. With limited computational resources, the requirement to generate these computationally expensive reforecast training datasets with a stable modeling system often conflicts with the desire to rapidly implement improvements in operational ensemble forecast systems.

Nonstatistical postprocessing techniques (objective 3.5) are also needed to produce reliable and skillful forecast uncertainty information about forecast variables of interest that are not directly predicted by numerical models or derived from statistical relationships (using statistical postprocessing techniques discussed under objective 3.4). Considering aviation as an example, a variety of groups [e.g., National Center for Atmospheric Research (NCAR) Research Applications Laboratory, Massachusetts Institute of Technology Lincoln Laboratory] have developed algorithms for estimating aviation-related parameters, such as icing, turbulence, and ceiling, from weather model output (NCAR 2011). Many of these algorithms have been implemented for deterministic forecasts in the NWS at the Aviation Weather Center in Kansas City, Missouri. However, little has been done to develop, test, and verify algorithms that produce skillful and reliable probabilistic forecasts of these variables that are not normally observed.

The specific role of human forecasters in the day-to-day generation of probabilistic forecasts will depend on their ability to add value to raw and/or postprocessed ensemble model output. In general, the role of human forecasters likely will expand from the current routine preparation of single-value (deterministic) forecasts to monitoring, quality controlling, and interpreting probabilistic forecast guidance; identifying and assigning confidence to alternate forecast scenarios; and when appropriate (e.g., during high-impact events) manually modifying automated model guidance (Stuart et al. 2006, 2007; Novak et al. 2008; Sills 2009). Although most current forecast preparation systems and tools aiding human forecasters are focused on generating single-value forecasts, these new functions will require probabilistic forecast preparation systems (objective 3.6) and tools that allow humans to interpret and manipulate entire ensemble distributions.

Regardless of the specific role that human forecasters eventually assume in the operational generation of forecast uncertainty information, they will need training (objective 3.7). Although some basic training on the theoretical basis for ensemble prediction systems has been developed, more is needed to provide knowledge of the general underlying theory behind and the performance of ensemble prediction and other probabilistic systems, the weaknesses in current operational systems, and what can and cannot be corrected with statistical postprocessing. Forecasters will also need to be trained in the new uncertainty forecast preparation tools they will use in addition to how to collaborate with and assist users in interpreting and using uncertainty information in their decision processes (strategic goal 2).

The Enterprise also needs a comprehensive, agreed-upon set of standards and software algorithms for uncertainty verification (objective 3.8). Currently, forecast verification methods focus on verifying the best single-value forecast estimate. Probabilistic forecast verification techniques must be developed and/or applied that will assess the characteristics of uncertainty forecasts and provide quantitative feedback to ensemble developers, forecasters, service providers, and end users to aid in interpretation and decision making. Statistics generated from these techniques are needed to serve as a reference for user expectations, guide future improvements, and assess the value added during each step of the forecast process.

The final objective under strategic goal 3 (objective 3.9) is to make all of this forecast uncertainty information available to Enterprise partners, who can then communicate it to their users and customers either in its raw form or through value-added products, services, and information. Currently, hydrometeorological observations and forecast products and information flow, in various formats and via numerous push–pull technologies, from their originating sources to partners, customers, and other users inside and outside of the Enterprise. This direct-from-source-to-user information flow will not necessarily diminish in the future. However, more powerful computational and telecommunications technologies now are enabling "one stop" repositories of archived and real-time data and information. The NWS, for example, is already providing gridded mosaics of sensible surface weather elements in its National Digital Forecast Database (NDFD) (Glahn and Ruth 2003). This concept is expected to expand to include more parameters and four dimensions (three space dimensions and one time dimension). Moreover, the FAA, National Oceanic and Atmospheric Administration (NOAA), and other federal agency partners are envisioning using this weather information storage approach to support NextGen. This "four-dimensional weather information database" will contain real-time observation and forecast data. Initial NextGen requirements already state that all forecast products must have probabilistic attributes. The ultimate vision is for a four-dimensional environmental information database that includes comprehensive hydrometeorological as well as other Earth system observations, predictions, and related information for users to access. Comprehensive forecast uncertainty data and information will need to be included in the planning, deployment, and access of these database systems as they evolve.

Strategic goal 4. Enable forecast uncertainty research, development, and operations with supporting infrastructure. The purpose of strategic goal 4 is to provide the infrastructure that will be necessary to carry out the objectives under the other three strategic goals. Specifically, many of the objectives under strategic goals 1 and 2, such as predictability studies (objective 1.2), ensemble design (objective 1.3), operational ensemble initialization and prediction (objectives 3.1 and 3.2), and statistical postprocessing (objective 3.4), will require increases in high-performance computing (objective 4.1). Despite advances that may be possible by sharing multimodel ensemble forecast data among U.S. and international centers, the production of skillful and reliable probability products cannot be achieved fully without a large increase in computational resources dedicated to the production of improved uncertainty forecasts. Currently, the U.S. Enterprise does not focus as much high-performance computing on ensemble prediction systems as some other international hydrometeorological organizations. For example, the European Centre for Medium-Range Weather Forecasts (ECMWF) currently runs a larger global ensemble (51 members) compared to the NWS's National Centers for Environmental Predication (NCEP) global ensemble (21 members), at approximately 3 times higher resolution,[2] and includes the regular production of real-time reforecasts that can be used for calibration. Although NCEP runs its ensemble system 4 times daily to ECMWF's twice daily, it may take currently as much as 40 times[3] more computational resources for NCEP to fully match the ECMWF system.

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[2] Currently, the ECMWF global ensemble runs at T639 resolution for the first 10 days of its forecast and T319 thereafter. The NCEP global ensemble runs at T190 for its full 16-day forecast.

[3] The 40 times multiple is estimated based on the following: ECMWF's ensemble resolution is currently T639L62 and NCEP's ensemble resolution is T190L28—that is 3.36 times greater resolution for ECMWF in the horizontal and 2.14 times greater in the vertical. Neglecting differences in advection approach (discussed below), this means that ECMWF's ensemble is based on $3.36^3 \times 2.14 \cong 81$ times more calculations, including the proportionally reduced time step for ECMWF. ECMWF also generates 100 real-time members per day, whereas NCEP generates 84 real-time members per day. However, ECMWF also generates 90 reforecast members (5 members × 18 yr) each week, or an extra ~13 per day. So, ECMWF produces a factor of $(100 + 13)/ 84 = 1.34$ times more members. The total extra computational burden is thus $81 \times 1.34 \cong 109$ times more. Assuming roughly that ECMWF's semi-Lagrangian scheme allows a time step 3 times longer, this then indicates a ~36 times greater computational burden. There are many other factors neglected here: the sophistication and computational expense of different parameterization methods, the different computational expense of the Legendre transforms to grids, different data assimilation approaches, and so on. Nevertheless, we think 40 times greater is a reasonable rough estimate of the overall computational difference.

A readily accessible public archive of past operational ensemble forecasts and verification statistics is also needed (objective 4.2) to facilitate research (objectives 1.2 and 1.3), the calibration (statistical adjustment) of ensemble forecasts (objective 3.4), the ensemble technique development process, product development, and forecaster training. Currently, the NOAA Operational Model Archive and Distribution System (NOMADS; Rutledge et al. 2006) is an emerging Enterprise-wide resource for storing numerical forecast guidance. NOAA has a cooperative agreement with the Meteorological Service of Canada to share ensemble forecast information in NOMADS and is developing similar agreements to share forecasts with the U.S. Navy and Air Force. The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE; Bougeault et al. 2010) archives a base set of global medium-range ensemble forecast and analysis information from nine different forecast centers worldwide. However, more data storage is required.

Data access systems are needed (objective 4.3) that are capable of transferring very large amounts of data from forecast uncertainty providers to clients and/or that allow these data to be parsed into subsets, transformed, and reformatted prior to transfer to the client. A number of current projects are exploring facets of ensemble data access, including NOMADS, Unidata, and the Global Interactive Forecasting System.

A test bed is needed (objective 4.4) where developers, forecasters, and users can interact with and test forecast uncertainty products, services, and information prior to implementation. Although there is a nascent ensemble test bed within the Developmental Testbed Center (Toth et al. 2011), which focuses on testing and evaluating ensemble-related techniques, there is currently no facility that permits users (e.g., operational NWS and industry forecasters, emergency managers, other officials responsible for public safety, utility companies and other sectors, general public) to conveniently evaluate and critique experimental uncertainty products. Such a test bed would avoid the challenges of testing in a live production environment and provide a forum for feedback among providers and users before operational implementation.

Finally, users will need assistance (objective 4.5) defining the infrastructure they will need to use new forecast uncertainty information. Universities, industry, and consumers all have made significant and continuing investments in infrastructure. Technological advances keep increasing capabilities without increasing the cost. However, current user software systems are mostly oriented toward single deterministic forecasts. Software systems and decision aids that deal with a single-value forecast and no probabilistic information will need to be upgraded and optimized in a manner that most easily allows later improvement.

NEXT STEPS.

Likely, the most important next step for this Plan is to identify a lead to implement it. The ACUF believes strong leadership in organizing and motivating Enterprise resources and expertise will be necessary to reach the Plan's vision and goals and shift the nation successfully to a greater understanding and use of forecast uncertainty information. To this end, the committee endorses the recommendation in NRC (2006) for NOAA and, in particular, the NWS as the nation's public weather service to take on this leadership role. Furthermore, the ACUF recommends that the AMS Commission Steering Committee (CSC) as part of the CWCE monitor progress and provide executive oversight for this Plan because the CSC is a body of senior representatives from the entire Enterprise.

Another important next step is to develop an overarching strategy of how the Enterprise will resource and implement the proposed tasks. Examples of such a strategy would be 1) to attempt to establish a single large program, 2) to use the Plan to guide various independent but nevertheless connected projects, or 3) some combination of 1 and 2.

Activities under the second option are occurring already and have informed and are leveraging this Plan. For example, the National Unified Operational Prediction Capability (NUOPC) program (see www.weather.gov/nuopc/) is using the Plan to help build a national research and development (R&D) agenda that will be used to improve a tri-agency (NOAA, Navy, and Air Force) unified ensemble system. Another example is the national workshop on mesoscale probabilistic prediction, which was held in September 2009 and sponsored by NCAR and the NWS. The recommendations from this workshop support and extend modeling and enabling infrastructure objectives and tasks under strategic goals 3 and 4 in this Plan. Moreover, the workshop recommended the formation of working groups, lead by a national advisory committee, to perform the needed R&D effort and to use the Plan to help guide their activities.

Finally, although the implementation road map suggests sector roles and responsibilities and sector leadership for the various tasks in the Plan, the Plan itself is not programmatic in the sense of defining specific program/project plans with accompanying cost, schedule, and performance information. Defining these important programmatic details is also among the next steps in implementing the Plan and should be the purview and responsibility of Enterprise decision makers throughout the partnership.

ACKNOWLEDGMENTS. More than 60 professionals from government, industry, and academia volunteered to be members of the American Meteorological Society (AMS) Ad Hoc Committee on Uncertainty in Forecasts (ACUF) and contributed to the development of the Strategic Implementation Plan for Generating and Communicating Forecast Uncertainty. Thanks go to all of those individuals (see list provided in the Plan) who served on the committee, who wrote sections of the Plan, and who reviewed the Plan and this paper. Appreciation is also extended to the AMS Board on Enterprise Communication, Commission on the Weather and Climate Enterprise. The publication of this paper was supported by AccuWeather, Inc.; the Army Test and Evaluation Command; the Office of Naval Research; and the National Oceanic and Atmospheric Administration. The views expressed in this paper are those of the authors and do not necessarily represent those of their organizations.

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CLIMATE SCIENCE AND THE UNCERTAINTY MONSTER

BY J. A. CURRY AND P. J. WEBSTER

An exploration of ways to understand, assess and reason about uncertainty in climate science, with specific application to the IPCC assessment process.

Doubt is not a pleasant condition, but certainty is absurd.

—VOLTAIRE

Over the course of history, what seems unknowable and unimaginable to one generation becomes merely a technical challenge for a subsequent generation. The "endless frontier" of science (Bush 1945) advances as scientists extend what is possible both in theory and practice. Doubt and uncertainty about our current understanding is inherent at the knowledge frontier. While extending the knowledge frontier often reduces uncertainty, it leads inevitably to greater uncertainty as unanticipated complexities are discovered. A scientist's perspective of the knowledge frontier is described by Feynman (1988): "When a scientist does not know the answer to a problem, he is ignorant. When he has a hunch as to what the result is, he is uncertain. And when he is pretty damn sure of what the result is going to be, he is still in some doubt. We have found it of paramount importance that in order to progress, we must recognize our ignorance and leave room for doubt. Scientific knowledge is a body of statements of varying degrees of certainty—some most unsure, some nearly sure, but none absolutely certain."

How to understand and reason about uncertainty in climate science is a topic that is receiving increasing attention in both the scientific and philosophical literature. Such inquiry is paramount because of the challenges to climate science associated with the science–policy interface and its socioeconomic importance, as reflected by the Intergovernmental Panel for Climate Change (IPCC) assessment reports (all IPCC assessment reports are available online at www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1.)[1]

The "uncertainty monster" is a concept introduced by Van der Sluijs (2005) in an analysis of the different ways that the scientific community responds to uncertainties that are difficult to tame. The "monster" is the

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-10-3139.1

In final form 20 June 2011

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[1] The first–fourth assessment reports (ARs) are referred to here as FAR, SAR, TAR, AR4, plus the forthcoming AR5. Unless otherwise indicated, citations in the text refer to Working Group I reports.

confusion and ambiguity associated with knowledge versus ignorance, objectivity versus subjectivity, facts versus values, prediction versus speculation, and science versus policy. The uncertainty monster gives rise to discomfort and fear, particularly with regard to our reactions to things or situations we cannot understand or control, including the presentiment of radical unknown dangers. An adaptation of Van der Sluijs's strategies of coping with the uncertainty monster at the science–policy interface is described below.

- *Monster hiding.* Uncertainty hiding or the "never admit error" strategy can be motivated by a political agenda or because of fear that uncertain science will be judged as poor science by the outside world. Apart from the ethical issues of monster hiding, the monster may be too big to hide and uncertainty hiding enrages the monster.
- *Monster exorcism.* The uncertainty monster exorcist focuses on reducing the uncertainty through advocating for more research. In the 1990s, a growing sense of the infeasibility of reducing uncertainties in global climate modeling emerged in response to the continued emergence of unforeseen complexities and sources of uncertainties. Van der Sluijs (2005, p. 88) states that "monster-theory predicts that [reducing uncertainty] will prove to be vain in the long run: for each head of the uncertainty monster that science chops off, several new monster heads tend to pop up due to unforeseen complexities," analogous to the Hydra beast of Greek mythology.
- *Monster simplification.* Monster simplifiers attempt to transform the monster by subjectively quantifying and simplifying the assessment of uncertainty. Monster simplification is formalized in the IPCC TAR and AR4 by guidelines for characterizing uncertainty in a consensus approach consisting of expert judgment in the context of a subjective Bayesian analysis (Moss and Schneider 2000).
- *Monster detection.* The first type of uncertainty detective is the scientist who challenges existing theses and works to extend knowledge frontiers. The second type is the watchdog auditor, whose main concern is accountability, quality control, and transparency of the science. The third type is the merchant of doubt (Oreskes and Collins 2010), who distorts and magnifies uncertainties as an excuse for inaction for financial or ideological reasons.
- *Monster assimilation.* Monster assimilation is about learning to live with the monster and giving uncertainty an explicit place in the contemplation and management of environmental risks. Assessment and communication of uncertainty and ignorance, along with extended peer communities, are essential in monster assimilation. The challenge to monster assimilation is the ever-changing nature of the monster and the birth of new monsters.

This paper explores ways to understand, assess, and reason about uncertainty in climate science, with specific application to the IPCC assessment process. Section 2 describes the challenges of understanding and characterizing uncertainty in dynamical models of complex systems, including challenges to interpreting the ensemble of simulations for the twenty-first-century climate used in the IPCC assessment reports. Section 3 addresses some issues regarding reasoning about uncertainty and examines the treatment of uncertainty by the IPCC Assessment Reports. Section 4 addresses uncertainty in the detection and attribution of anthropogenic climate change. And finally, section 5 introduces some ideas for monster taming strategies at the levels of institutions, individual scientists, and communities.

UNCERTAINTY OF CLIMATE MODELS.

Synergy means behavior of whole systems unpredicted by the behavior of their parts.

—R. Buckminster Fuller

Climate model complexity arises from the nonlinearity of the equations' high dimensionality (millions of degrees of freedom) and the linking of multiple subsystems. Computer simulations of the complex climate system can be used to represent aspects of climate that are extremely difficult to observe, experiment with theories in a new way by enabling hitherto infeasible calculations, understand a system of equations that would otherwise be impenetrable, and explore the system to identify unexpected outcomes (e.g., Muller 2010).

Imperfect models.

The future ain't what it used to be.

—Yogi Berra

Model imperfection is a general term that describes our limited ability to simulate climate and is categorized here in terms of model inadequacy and model uncertainty. Model inadequacy reflects our limited understanding of the climate system, inadequacies of numerical solutions employed in computer models, and the fact that no model can be structurally identical to the actual system (e.g., Stainforth et al. 2007). Model structural form is the conceptual modeling of the physical system (e.g., dynamical equations, initial and boundary conditions), including the selection of subsystems to include (e.g., stratospheric chemistry, ice sheet dynamics). In addition to insufficient understanding of the system, uncertainties in model structural form are introduced as a pragmatic compromise between numerical stability and fidelity to the underlying theories, credibility of results, and available computational resources.

UNCERTAINTY LEXICON

The nature of uncertainty is often expressed by the distinction between epistemic uncertainty and ontic uncertainty.

Epistemic uncertainty is associated with imperfections of knowledge, which may be reduced by further research and empirical investigation. Examples include limitations of measurement devices and insufficient data. Epistemic uncertainties in models include missing or inadequately treated processes and errors in the specification of boundary conditions.

Ontic (often referred to as *aleatory*) *uncertainty* is associated with inherent variability or randomness.

Natural internal variability of the climate system contributes to ontic uncertainty in the climate system. Ontic uncertainties are by definition irreducible.

Walker et al. (2003) provides a complete logical structure of the level of uncertainty, characterized as a progression between deterministic understanding and total ignorance: statistical uncertainty, scenario uncertainty, and recognized ignorance.

Statistical uncertainty is the aspect of uncertainty that is described in statistical terms. An example of statistical uncertainty is measurement uncertainty, which can be due to sampling error or inaccuracy or imprecision in measurements.

Scenario uncertainty implies that it is not possible to formulate the probability of occurrence of one particular outcome. A scenario is a plausible but unverifiable description of how the system and/or its driving forces may develop over time. Scenarios may be regarded as a range of discrete possibilities with no a *priori allocation* of likelihood.

Recognized ignorance refers to fundamental uncertainty in the mechanisms being studied and a weak scientific basis for developing scenarios. *Reducible ignorance* may be resolved by conducting further research, whereas *irreducible ignorance* implies that research cannot improve knowledge.

An alternative taxonomy for levels of uncertainty is illustrated by this quote from U.S. Secretary of Defense Donald Rumsfeld (U.S. DOD 2011): "[A]s we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we do not know we do not know. And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones."

Model uncertainty is associated with uncertainty in model parameters and subgrid parameterizations, and also with uncertainty in initial conditions. Uncertainties in parameter values include uncertain constants and other parameters that are largely contained in subgrid-scale parameterizations (e.g., boundary layer turbulence, cloud microphysics), and parameters involved in ad hoc modeling to compensate for the absence of neglected factors. Initial condition uncertainty arises in simulations of nonlinear and chaotic dynamical systems (e.g., Palmer et al. 2005). If the initial conditions are not known exactly, then the forecast trajectory will diverge from the actual trajectory, and it cannot be assumed that small perturbations have small effects. As such, model uncertainty includes epistemic uncertainty in parameter values and both epistemic and ontic uncertainty in initial conditions.

Ensemble methods are a brute force approach to representing model parameter and initial condition uncertainty (for an overview, see Parker 2010). Rather than conducting a single simulation, multiple simulations are run that sample some combination of different initial conditions, model parameters and parameterizations, and model structural forms.

While the ensemble method used in weather and climate predictions is inspired by Monte Carlo approaches, the application of a traditional Monte Carlo approach far outstrips computational capacity owing to the very large number of possible combinations required to fully represent climate model parameter and initial condition uncertainty. A high level of model complexity and high model resolution precludes large ensembles. Stochastic parameterization methods are being introduced (e.g., Palmer 2001) to characterize parameter and parameterization uncertainty, reducing the need to conduct ensemble simulations to explore parameter and parameterization uncertainty.

Model outcome uncertainty, also referred to as prediction error, arises from the propagation of the aforementioned uncertainties through the model simulation and is evidenced by the simulated outcomes. Model prediction error can be evaluated against known analytical solutions, comparisons with other simulations, and/or comparison with observations. Reducing prediction error is a fundamental objective of model calibration. Calibration is necessary to address parameters that are unknown or inapplicable at the model resolution, and also in the linking of submodels. As the complexity, dimensionality, and modularity of a model grow, model calibration becomes unavoidable and an increasingly important issue. Model calibration is accomplished by kludging (or tuning), which is "an inelegant, botched together piece of program; something functional but somehow messy and unsatisfying, a piece of program or machinery which works up to a point" (Lenhard and Winsberg 2011, p. 121). A kludge required in one model may not be required in another model that has greater structural adequacy or higher resolution. Continual ad hoc adjustment of the model (calibration) provides a means for the model to avoid being falsified; Occam's razor presupposes that the model least dependent on continual ad hoc modification is to be preferred.

A serious challenge to improving complex nonlinear models is that model complexity and analytic impenetrability precludes the precise evaluation of the location of parameter(s) that are producing the prediction error (Lenhard and Winsberg 2010). For example, if a model is producing shortwave surface radiation fluxes that are substantially biased relative to observations, it is impossible to determine whether the error arises from the radiative transfer model, incoming solar radiation at the top of the atmosphere, concentrations of the gases that absorb shortwave radiation, physical and chemical properties of the aerosols in the model, morphological and microphysical properties of the clouds, convective parameterization that influences the distribution of water vapor and clouds, and/or characterization of surface reflectivity. Whether a new parameterization module adds to or subtracts from the overall reliability of the model may have more to do with some entrenched features of model calibration than it does with that module's fidelity to reality when considered in isolation.

Confidence and credibility.

All models are wrong, but some are useful.

—George E. P. Box

Confidence is a degree of certainty that a particular model is effective or useful. Confidence is inspired by the model's relation to theory and physical understanding of the processes involved, sensitivity of the simulations to model structure, the nature of the ad hoc adjustments and calibration, extensive exploration of model uncertainty, consistency of the simulated responses, and the ability of the model and model components to simulate historical observations (e.g., Knutti 2008). User confidence in a forecast model system depends critically on the confirmation of forecasts, both using historical data (hindcasts, in-sample) and actual forecasts (out-of-sample observations). Parker (2009) argues that instances of fit between model output and observational data do not confirm the models themselves, but rather hypotheses about the adequacy of climate models for particular purposes. Hence, model validation strategies depend on the intended application of the model. However, there is no generally agreed upon protocol for the validation of climate models (e.g., Guillemot 2010).

User confidence in a forecast model depends critically on the confirmation of forecasts, both using historical data (hindcasts, in-sample) and out-of-sample observations (forecasts). Confirmation with out-of-sample observations is possible for forecasts that have a short time horizon that can be compared with out-of-sample observations (e.g., weather forecasts). Unless the model can capture or bound a phenomenon in hindcasts and previous forecasts, there is no expectation that the model can quantify the same phenomena in subsequent forecasts. Capturing the phenomena in hindcasts and previous forecasts does not in any way guarantee the ability of the model to capture the phenomena in the future, but it is a necessary condition (Smith 2002). If the distance of future simulations from the established range of model validity is small, then it reasonable to extend established confidence in the model to the perturbed future state. Extending such confidence requires that no crucial feedback mechanisms are missing from the model (Smith 2002).

Even for in-sample validation, there is no straightforward definition of model performance for complex nondeterministic models having millions of degrees of freedom (e.g., Guillemot 2010). Because the models are not deterministic, multiple simulations are needed to compare with observations, and the number of simulations conducted by modeling centers are insufficient to establish a robust mean; hence, bounding box approaches (assessing whether the range of the ensembles bounds the observations; Judd et al. 2007) are arguably a better way to establish empirical adequacy. A further complication arises if datasets used in the model evaluation process are the same as those used for calibration, which gives rise to circular reasoning (confirming the antecedent) in the evaluation process.

On the subject of confidence in climate models, Knutti (2008, p. 2654) summarizes, "So the best we can hope for is to demonstrate that the model does not violate our theoretical understanding of the system and that it is consistent with the available data within the observational uncertainty."

Simulations of the twenty-first-century climate.

There are many more ways to be wrong in a 10^6 dimensional space than there are ways to be right.

—Leonard Smith

What kind of confidence can we have in the simulations of scenarios for the twenty-first century? Since projections of future climate relate to a state of the system that is outside the range of model validity, it is therefore impossible to either calibrate the model for the forecast regime of interest or confirm the usefulness of the forecasting process. The problem is further exacerbated by the lifetime of an individual model version being substantially less than the prediction lead time (Smith 2002).

If the distance of future simulations from the established range of model validity is small, then it reasonable to extend established confidence in the model to the perturbed future state. In effect, such confidence requires that we assume that nothing happens that takes the model farther beyond its range of validity, and that no crucial feedback mechanisms are missing from the model (Smith 2002). Of particular relevance to simulations with increased greenhouse gases is the possibility that slow changes in the forcing may push the model beyond a threshold and induce a transition to a second equilibrium.

A key issue in assessing model adequacy for twenty-first-century climate simulations is the inclusion of longer time-scale processes, such as the global carbon cycle and ice sheet dynamics. In addition to these known unknowns, there are other processes that we have some hints of but currently have no way of quantifying (e.g., methane release from thawing permafrost). Confidence established in the atmospheric dynamical core as a result of the extensive cycles of evaluation and improvement of weather forecast models is important, but other factors become significant in climate models that have less import in weather models, such as mass conservation and cloud and water vapor feedback processes.

Given the inadequacies of current climate models, how should we interpret the multimodel ensemble simulations of the twenty-first-century climate used in the IPCC assessment reports? This ensemble of opportunity is composed of models with generally similar structures but different parameter choices and calibration histories (for an overview, see Knutti et al. 2008; Hargreaves 2010). McWilliams (2007) and Parker (2010) argue that current climate model ensembles are not designed to sample representational uncertainty in a thorough or strategic way. Stainforth et al. (2007) argue that model inadequacy and an inadequate number of simulations in the ensemble preclude producing meaningful probability density functions (PDFs) from the frequency of model outcomes of future climate. Nevertheless, as summarized by Parker (2010), it is becoming increasingly common for results from individual multimodel and perturbed physics simulations to be transformed into probabilistic projections of future climate, using Bayesian and other techniques. Parker argues that the reliability of these probabilistic projections is unknown, and in many cases they lack robustness. Knutti et al. (2008) argues that the real challenge lies more in how to interpret the PDFs than in whether they should be constructed in the first place. Stainforth et al. (2007) warns against overinterpreting current model results since they could be contradicted by the next generation of models, undermining the credibility of the new generation of model simulations.

Stainforth et al. (2007) emphasize that models can provide useful insights without being able to provide probabilities, by providing a lower bound on the maximum range of uncertainty and a range of possibilities to be considered. Kandlikar et al. (2005) argue that when sources of uncertainty are well understood, it can be appropriate to convey uncertainty via full PDFs; however, in other cases, it will be more appropriate to offer only a range in which one expects the value of a predictive variable to fall with some specified probability, or to indicate the expected sign of a change without assigning a magnitude. They argue that uncertainty should be expressed using the most precise means that can be justified, but that unjustified more precise means should not be used.

UNCERTAINTY AND THE IPCC.

You are so convinced that you believe only what you believe that you believe, that you remain utterly blind to what you really believe without believing you believe it.

—Orson Scott Card, *Shadow of the Hegemon*

How to reason about uncertainties in the complex climate system and its computer simulations is not simple or obvious. Scientific debates involve controversies over the value and importance of particular classes of evidence as well as disagreement about the appropriate logical framework for linking and assessing the evidence. The IPCC faces a daunting challenge with regard to characterizing and reasoning about uncertainty, assessing the quality of evidence, linking the evidence into arguments, identifying areas of ignorance, and assessing confidence levels.

Characterizing uncertainty.

> *A long time ago a bunch of people reached a general consensus as to what's real and what's not and most of us have been going along with it ever since.*
>
> —Charles de Lint

Over the course of four assessment reports, the IPCC has given increasing attention to reporting uncertainties (e.g., Swart et al. 2009). The "guidance paper" by Moss and Schneider (2000) recommended steps for assessing uncertainty in the IPCC assessment reports and a common vocabulary to express quantitative levels of confidence based on the amount of evidence (number of sources of information) and the degree of agreement (consensus) among experts (see sidebar for vocabulary).

The IPCC guidance for characterizing uncertainty for the AR4 (WMO 2005) describes three approaches for indicating confidence in a particular result and/or that the likelihood that a particular conclusion is correct:

1) A qualitative level-of-understanding scale describes the level of scientific understanding in terms of the amount of evidence available and the degree of agreement among experts. There can be limited, medium, or much evidence, and agreement can be low, medium, or high.
2) A quantitative confidence scale estimates the level of confidence for a scientific finding and ranges from "very high confidence" (9 in 10 chance) to "very low confidence" (less than 1 in 10 chance).
3) A quantitative likelihood scale represents "a probabilistic assessment of some well-defined outcome having occurred or occurring in the future." The scale ranges from "virtually certain" (greater than 99% probability) to "exceptionally unlikely" (less than 1% probability).

Oppenheimer et al. (2007), Webster (2009), Petersen (2006), and Kandlikar et al. (2005) argue that future IPCC efforts need to be more thorough about describing sources and types of uncertainty, making the uncertainty analysis as transparent as possible. The InterAcademy Council (IAC; http://reviewipcc.interacademycouncil.net/) reviewed the IPCC's performance on characterizing uncertainty. In response to concerns raised in the review, the IAC made the following recommendations regarding the IPCC's treatment of uncertainty:

- "Each Working Group should use the qualitative level-of-understanding scale in its Summary for Policymakers and Technical Summary, as suggested in IPCC's uncertainty guidance for the Fourth Assessment." This is a key element of uncertainty monster detection.
- "Chapter Lead Authors should provide a traceable account of how they arrived at their ratings for level of scientific understanding and likelihood that an outcome will occur." Failure to provide a traceable account is characteristic of uncertainty monster hiding.
- "Quantitative probabilities (as in the likelihood scale) should be used to describe the probability of well-defined outcomes only when there is sufficient evidence. Authors should indicate the basis for assigning a probability to an outcome or event (e.g., based on measurement, expert judgment, and/or model runs)." Using quantitative probabilities when there is insufficient evidence is uncertainty monster simplification.

The recommendations made by the IAC concerning the IPCC's characterization of uncertainty are steps in the right direction in terms of dealing with the uncertainty monster. Curry (2011a) further argued that a concerted effort by the IPCC is needed to identify better ways of framing the climate change problem, exploring and characterizing uncertainty, reasoning about uncertainty in the context of evidence-based logical hierarchies, and eliminating bias from the consensus building process itself.

Reasoning about uncertainty.

> *It is not so much that people hate uncertainty, but rather that they hate losing.*
>
> —Amos Tversky

The IPCC characterization of characterization is based upon a consensus building process that is an exercise in collective judgment in areas of uncertain knowledge. The general reasoning underlying the IPCC's arguments for anthropogenic climate change combines a compilation of evidence with subjective Bayesian reasoning. This process is described by Oreskes (2007) as presenting a "consilience of evidence" argument, which consists of independent lines of evidence that are explained by the same theoretical account.

Given the complexity of the climate problem, expert judgments about uncertainty and confidence levels are made by the IPCC on issues that are dominated by unquantifiable uncertainties. Curry (2011a) argues that because of the complexity of the issues, individual experts use different mental models for evaluating the interconnected evidence. Biases can abound when reasoning and making judgments about such a complex problem. Bias can occur as a result of excessive reliance on a particular piece of evidence, the presence of cognitive biases in heuristics, failure to account for indeterminacy and ignorance, and logical fallacies and errors, including circular reasoning. The IAC (2010, p. 41) states that "studies suggest that informal elicitation measures, especially those designed to reach consensus, lead to different assessments of probabilities than formal measures. Informal procedures often result in probability distributions that place less weight in the tails of the distribution than formal elicitation methods, possibly understating the uncertainty associated with a given outcome."

Oreskes (2007) draws an analogy for the consilience of evidence approach with what happens in a legal case. Continuing with the legal analogy, Johnston (2010) characterized the IPCC's arguments as a legal brief, designed to persuade, in contrast to a legal memo that is intended to objectively assess both sides. Along the lines of a legal memo, Curry (2011a) argues that the consilience of evidence argument is not convincing unless it includes parallel evidence-based analyses for competing hypotheses, and hence a critical element in uncertainty monster detection. Any evidence-based argument that is more inclined to admit one type of evidence or argument rather than another tends to be biased. Parallel evidence-based analysis of competing hypotheses provides a framework whereby scientists with a plurality of viewpoints participate in an assessment. In a Bayesian analysis with multiple lines of evidence, it is conceivable that there are multiple lines of evidence that produce a high confidence level for each of two opposing arguments, which is referred to as the ambiguity of competing certainties. If uncertainty and ignorance are acknowledged adequately, then the competing certainties disappear. Disagreement then becomes the basis for focusing research in a certain area, and so moves the science forward.

UNCERTAINTY IN THE ATTRIBUTION OF TWENTIETH-CENTURY CLIMATE CHANGE.

Give me four parameters, and I can fit an elephant. Give me five, and I can wiggle its trunk.

—John von Neumann

Arguably the most important conclusion of IPCC AR4 is the following statement: "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC 2007, p. 10). This section raises issues regarding the uncertainties that enter into the attribution argument, ambiguities in the attribution statement and apparent circular reasoning, and lack of traceability of the "very likely" likelihood assessment.

IPCC's detection and attribution argument.

What we observe is not nature itself, but nature exposed to our method of questioning.

—Werner Karl Heisenberg

The problem of attributing climate change is intimately connected with the detection of climate change. A change in the climate is "detected" if its likelihood of occurrence by chance due to internal variability alone is determined to be small. Knowledge of internal climate variability is needed for both detection and attribution. Because the instrumental record is too short to give a well-constrained estimate of internal variability, internal climate variability is usually estimated from long control simulations from coupled climate models. The IPCC AR4 (Hegerl et al. 2007, p. 668) formulates the problem of attribution to be: "In practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is 'consistent with the estimated responses to the given combination of anthropogenic and natural forcing' and 'not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings'" (Mitchell et al. 2001, p. 700).

Detection and attribution analyses use objective statistical tests to assess whether observations contain evidence of the expected responses to external forcing that is distinct natural internal variability. Expected responses, or "fingerprints," are determined from climate models and physical understanding of the climate system. Formal Bayesian reasoning is used to some extent by the IPCC in making inferences about detection and attribution. The reasoning process used in assessing likelihood in the attribution statement is described by this statement from the AR4 (Hegerl et al. 2007, p. 669):

> The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgment is required to give a calibrated assessment of whether a specific cause is responsible for a given

> climate change. The assessment approach used in this chapter is to consider results from multiple studies using a variety of observational data sets, models, forcings and analysis techniques. The assessment based on these results typically takes into account the number of studies, the extent to which there is consensus among studies on the significance of detection results, the extent to which there is consensus on the consistency between the observed change and the change expected from forcing, the degree of consistency with other types of evidence, the extent to which known uncertainties are accounted for in and between studies, and whether there might be other physically plausible explanations for the given climate change. Having determined a particular likelihood assessment, this was then further downweighted to take into account any remaining uncertainties, such as, for example, structural uncertainties or a limited exploration of possible forcing histories of uncertain forcings. The overall assessment also considers whether several independent lines of evidence strengthen a result.

The IPCC AR4 (Hegerl et al. 2007) describes two types of simulation methods that have been used in detection and attribution studies. The first method is a "forward calculation" that uses best estimates of external changes in the climate system (forcings) to simulate the response of the climate system using a climate model. These forward calculations are then directly compared to the observed changes in the climate system. The second method is an "inverse calculation," whereby the magnitude of uncertain model parameters and applied forcing is varied to provide a best fit to the observational record. While the exact reasoning underlying the IPCC's likelihood assessment is unclear, the important role of coupled climate models in the assessment is indicated by the fact that 12 of the 14 figures in sections 9.2–9.4 in Hegerl et al. (2007) are based upon the results of climate model simulations.

Whereas all of the climate model simulations and various attribution studies agree that the warming observed since 1970 can only be reproduced using anthropogenic forcings, models and attribution analyses disagree on the relative importance of solar, volcanic, and aerosol forcing in the earlier part of the twentieth century (section 9.4.1 in Hegerl et al. 2007). The substantial warming during the period 1910–40 has been attributed by nearly all the modeling groups to some combination of increasing solar irradiance and a lack of major volcanic activity. The cooling and leveling off of average global temperatures during the 1950s and 1960s is attributed primarily to aerosols from fossil fuels and other sources, when the greenhouse warming was overwhelmed by aerosol cooling.

Sources of uncertainty.

Not only does God play dice, but sometimes he throws the dice where we can't see them.

—Stephen Hawking

Attribution of observed climate change is affected by errors and uncertainties in the prescribed external forcing and in the model's capability to simulate both the response to the forcing (sensitivity) and decadal-scale natural internal variability. Uncertainties in the model and forcing are acknowledged by the AR4 (Hegerl et al. 2007, p. 669): "Ideally, the assessment of model uncertainty should include uncertainties in model parameters (e.g., as explored by multi-model ensembles), and in the representation of physical processes in models (structural uncertainty). Such a complete assessment is not yet available, although model intercomparison studies (chapter 8) improve the understanding of these uncertainties. The effects of forcing uncertainties, which can be considerable for some forcing agents such as solar and aerosol forcing (section 9.2), also remain difficult to evaluate despite advances in research."

The level of scientific understanding of radiative forcing is ranked by the AR4 (Table 2.11 in Forster et al. 2007) as high only for the long-lived greenhouse gases, but it is ranked as low for solar irradiance, aerosol effects, stratospheric water vapor from CH_4, and jet contrails. Radiative forcing time series for the natural forcings (solar, volcanic aerosol) are reasonably well known for the past 25 years, with estimates farther back in time having increasingly large uncertainties.

Based upon new and more reliable solar reconstructions, the AR4 (Forster et al. 2007, section 2.7.1.2) concluded that the increase in solar forcing during the period 1900–80 used in the AR3 reconstructions is questionable and that the direct radiative forcing due to an increase in solar irradiance is reduced substantially by the AR3. However, consideration of Table S9.1 in the Hegerl et al. (2007) shows that each climate model used outdated solar forcing (from the AR3) that was assessed to substantially overestimate the magnitude of the trend in solar forcing prior to 1980. The IPCC AR4 (Hegerl et al. 2007, p. 679) states that "while the 11-year solar forcing cycle is well documented, lower-frequency variations in solar forcing are highly uncertain." Furthermore, "large uncertainties associated with estimates of past solar forcing (section 2.7.1) and omission of some chemical and dynamical response mechanisms (Gray et al., 2005) make it difficult to reliably estimate the contribution of solar forcing to warming over the 20th century."

The greatest uncertainty in radiative forcing is associated with aerosols, particularly the aerosol indirect effect, whereby aerosols influence cloud radiative properties. Consideration of Fig. 2.20 of the AR4 (Forster et al. 2007) shows that, given the uncertainty in aerosol forcing, the magnitude of the aerosol forcing (which is negative, or cooling) could rival the forcing from long-lived greenhouse gases (positive, or warming). The twentieth-century aerosol forcing used in most of the AR4 model simulations (Forster et al. 2007, section 9.2.1.2) relies on inverse calculations of aerosol optical properties to match climate model simulations with observations. The only constraint on the aerosol forcing used in the AR4 attribution studies is that the derived forcing should be within the bounds of forward calculations that determine aerosol mass from chemical transport models, using satellite data as a constraint. The inverse method effectively makes aerosol forcing a tunable parameter (kludge) for the model, particularly in the presatellite era. Further, key processes associated with the interactions between aerosols and clouds are either neglected or treated with simple parameterizations in climate model simulations evaluated in the AR4.

Given the large uncertainties in forcings and model inadequacies in dealing with these forcings, how is it that each model does a credible job of tracking the twentieth-century global surface temperature anomalies (Fig. 9.5 in Hegerl et al. 2007)? Schwartz (2004) notes that the intermodel spread in modeled temperature trend expressed as a fractional standard deviation is much less than the corresponding spread in either model sensitivity or aerosol forcing, and this comparison does not consider differences in solar and volcanic forcing. This agreement is accomplished through inverse calculations, whereby modeling groups can select the forcing dataset and model parameters that produce the best agreement with observations. While some modeling groups may have conducted bona fide forward calculations without any a posteriori selection of forcing datasets and model parameters to fit the twentieth-century time series of global surface temperature anomalies, the available documentation on each model's tuning procedure and rationale for selecting particular forcing datasets is not generally available.

The inverse calculations can mask variations in sensitivity among the different models. If a model's sensitivity is high, then greater aerosol forcing is used to counter the greenhouse warming, and vice versa for low model sensitivity (Kiehl 2007). Schwartz (2004) argues that uncertainties in aerosol forcing must be reduced at least three-fold for uncertainty in climate sensitivity to be meaningfully reduced and bounded. Further, kludging and neglect of ontic uncertainty in the tuning can result in a model that is over- or undersensitive to certain types or scales of forcing.

With regard to the ability of climate models to simulate natural internal variability on decadal time scales, "there has been little work evaluating the amplitude of Pacific decadal variability in [coupled climate models]" (Randall et al. 2007, p. 621). Whereas most climate models simulate something that resembles the meridional overturning circulation (MOC), the mechanisms "that control the variations in the MOC are fairly different across the ensemble of [coupled climate models]" (p. 621). Comparison of the power spectra of observed and modeled global mean temperatures in Fig. 9.4 of Hegerl et al. (2007) shows that all models underestimate the amplitude of variability on periods of 40–70 yr, which encompasses key modes of multidecadal natural internal variability, such as the Pacific decadal oscillation and the Atlantic multidecadal oscillation.

Bootstrapped plausibility.

> *If it was so, it might be, and if it were so, it would be; but as it isn't it ain't. That's logic!*
>
> —Charles Lutwidge Dodgson
> (Lewis Carroll)

Bootstrapped plausibility (Agassi 1974) occurs with a proposition that is rendered plausible that in turn lends plausibility to some of the proposition's more doubtful supporting arguments. As such, bootstrapped plausibility occurs in the context of circular reasoning, which is fallacious because of a flawed logical structure whereby the proposition to be proved is implicitly or explicitly assumed in one of the premises. This subsection argues that the IPCC's detection and attribution arguments involve circular reasoning, and that confidence in the evidence and argument is elevated by bootstrapped plausibility.

Consider the following argument that apparently underlies the general reasoning behind the AR4's attribution statement:

1) *Detection.* Climate change in the latter half of the twentieth century is detected based primarily upon increases in global surface temperature

anomalies that are far larger than can be explained by natural internal variability.

2) *Confidence in detection.* The quality of agreement between model simulations with twentieth-century forcing and observations supports the likelihood that models are adequately simulating the magnitude of natural internal variability on decadal to century time scales. From Hegerl et al. 2007, p. 693): "However, models would need to underestimate variability by factors of over two in their standard deviation to nullify detection of greenhouse gases in near-surface temperature data (Tett et al. 2002), which appears unlikely given the quality of agreement between models and observations at global and continental scales (Figs. 9.7 and 9.8) and agreement with inferences on temperature variability from NH temperature reconstructions of the last millennium."
3) *Attribution.* Attribution analyses, including climate model simulations for the twentieth-century climate, that combine natural and anthropogenic forcing agree much better with observations than simulations that include only natural forcing. From Hegerl et al. (2007, p. 684): "The fact that climate models are only able to reproduce observed global mean temperature changes over the 20th century when they include anthropogenic forcings, and that they fail to do so when they exclude anthropogenic forcings, is evidence for the influence of humans on global climate."
4) *Confidence in attribution.* Detection and attribution results based on several models or several forcing histories suggest that the attribution of a human influence on temperature change during the latter half of the twentieth century is a robust result. From Hegerl et al. (2007, p. 669): "Detection and attribution results based on several models or several forcing histories do provide information on the effects of model and forcing uncertainty. Such studies suggest that while model uncertainty is important, key results, such as attribution of a human influence on temperature change during the latter half of the 20th century, are robust."

The strong agreement between forced climate model simulations and observations for the twentieth century (premise 3) provides bootstrapped plausibility to the models and the external forcing data. However, this strong agreement depends heavily on inverse modeling, whereby forcing datasets and/or model parameters are selected based upon the agreement between models and the time series of twentieth-century observations. Further confidence in the models is provided by premise 4, even though the agreement of different models and forcing datasets arises from the selection of forcing datasets and model parameters by inverse calculations designed to agree with the twentieth-century time series of global surface temperature anomalies. This agreement is used to argue that "Detection and attribution studies using such simulations suggest that results are not very sensitive to moderate forcing uncertainties" (Hegerl et al. 2007, p. 678).

Confidence in the climate models that is elevated by inverse calculations and bootstrapped plausibility is used as a central premise in the argument that climate change in the latter half of the twentieth century is much greater than can be explained by natural internal variability (premise 1). Premise 1 underlies the IPCC's assumption (Hegerl et al. 2007, p. 684) that "Global mean and hemispheric-scale temperatures on multi-decadal time scales are largely controlled by external forcings (Stott et al. 2000)" and not natural internal variability. In effect, the IPCC's argument has eliminated multidecadal natural internal variability as a causative factor for twentieth-century climate change. Whereas each model demonstrates some sort of multidecadal variability (which might be of a reasonable amplitude or associated with the appropriate mechanisms), the ensemble averaging process filters out the simulated natural internal variability since there is no temporal synchronization in the simulated chaotic internal oscillations among the different ensemble members.

The IPCC's detection and attribution method is meaningful to the extent that the models agree with observations against which they were not tuned and to the extent that the models agree with each other in terms of attribution mechanisms. The AR4 has demonstrated that greenhouse forcing is a plausible explanation for warming in the latter half of the twentieth century, but it cannot rule out substantial warming from other causes, such as solar forcing and internal multidecadal ocean oscillations owing to the circular reasoning and to the lack of convincing attribution mechanisms for the warming during 1910–40 and the cooling during the 1940s and 1950s.

Bootstrapped plausibility and circular reasoning in detection and attribution arguments can be avoided by the following:

- Using the same best estimate of forcing components from observations or forward modeling for multimodel ensembles
- Conducting tests of the sensitivity to uncertainties associated with the forcing datasets using a single model

- Improving understanding of multidecadal natural internal variability and the models' ability to simulate its magnitude
- Improving detection and attribution schemes to account for the models' inability to simulate the timing of phases of natural internal oscillations and the meridional overturning circulation
- Considering the broad range of confounding factors in assessing likelihood and confidence, including observational errors, model errors and uncertainties, uncertainties in internal variability, and inadequacies in the fingerprinting methodology

The experimental design being undertaken for the Coupled Model Intercomparison Project phase 5 simulations (Taylor et al. 2011) to be used in the IPCC AR5 shows improvements that should eliminate some of the circular reasoning that was evident in the AR4 attribution argument. In the CMIP5 simulations, the use of specific best-estimate datasets of forcing for solar and aerosols is recommended. The National Center for Atmospheric Research (NCAR) Community Climate System Model twentieth-century simulations for CMIP5 (Gent et al. 2011) arguably qualifies as a completely forward calculation, with forcing datasets being selected a priori and no tuning of parameters in the coupled model to the twentieth-century climate other than the sea ice albedo and the low cloud relative humidity threshold. The results of NCAR's CMIP5 calculations show that after 1970, the simulated surface temperature increases faster than the data, so that by 2005 the model anomaly is 0.4°C larger than the observed anomaly. Understanding this disagreement should provide an improved understanding of the model uncertainties and uncertainties in the attribution of the recent warming. This disagreement implies that the detection and attribution argument put forth in the AR4 that was fundamentally based on the good agreement between models and observations will not work in the context of at least some of the CMIP5 simulations.

Since no traceable account is given in the AR4 of how the likelihood assessment in the attribution statement was reached, it is not possible to determine what the qualitative judgments of the lead authors were on the methodological reliability of their claim. Further, the attribution statement itself is at best imprecise and at worst ambiguous: what does "most" mean—51% or 99%? The high likelihood of the imprecise "most" seems rather meaningless (uncertainty monster simplification). From the IAC: "In the Committee's view, assigning probabilities to imprecise statements is not an appropriate way to characterize uncertainty."

Logic of the attribution statement.

> *Often, the less there is to justify a traditional custom, the harder it is to get rid of it.*
>
> —Mark Twain

Over the course of the four IPCC assessments, the attribution statement has evolved in the following way:

- FAR (IPCC 1990, p. xii): "The size of the warming over the last century is broadly consistent with the prediction by climate models, but is also of the same magnitude as natural climate variability . . . Thus the observed increase could be largely due to this natural variability: alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more."
- SAR (IPCC 1995, p. 4): "The balance of evidence suggests a discernible human influence on global climate."
- TAR (IPCC 2001, p. 5): "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."
- AR4 (IPCC 2007, p.10): "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations."

The attribution statements have evolved from "discernible" in the SAR to "most" in the TAR and AR4, demonstrating an apparent progressive exorcism of the uncertainty monster. The attribution statements are qualitative and imprecise in the sense of using words such as "discernible" and "most." The AR4 attribution statement is qualified with a "very likely" likelihood. As stated previously by the IAC, assigning probabilities to imprecise statements is not an appropriate way to characterize uncertainty.

The utility of the IPCC's attribution statement is aptly summarized by this quote from a document discussing climate change and national security (Rogers and Gulledge 2010, p. 19): "For the past 20 years, scientists have been content to ask simply whether ***most*** of the observed warming was caused by human activities. But is the percentage closer to 51 percent or to 99 percent? This question has not generated a great deal of discussion within the scientific community, perhaps because it is not critical to further progress in understanding the climate system. In the policy arena, however, this question is asked often and largely goes unanswered."

The logic of the IPCC AR4 attribution statement is discussed by Curry (2011b). Curry argues that the attribution argument cannot be well formulated in the context of Boolean logic or Bayesian probability. Attribution (natural vs anthropogenic) is a shades-of-gray issue and not a black or white, 0 or 1 issue, or even an issue of probability. Toward taming the attribution uncertainty monster, Curry argues that fuzzy logic provides a better framework for considering attribution, whereby the relative degrees of truth for each attribution mechanism can range in degree between 0 and 1, thereby bypassing the problem of the excluded middle. There is general agreement that the percentages of warming each attributed to natural and anthropogenic causes is less than 100% and greater than 0%. The challenge is to assign likelihood values to the distribution of the different combinations of percentage contributions of natural and anthropogenic contributions. Such a distribution may very well show significant likelihood in the vicinity of 50/50, making a binary demarcation at the imprecise "most" a poor choice.

TAMING THE UNCERTAINTY MONSTER.

I used to be scared of uncertainty; now I get a high out of it.

—Jensen Ackles

Symptoms of an enraged uncertainty monster include increased levels of confusion, ambiguity, discomfort, and doubt. Evidence that the monster is currently enraged includes doubt that was expressed particularly by European policy makers at the climate negotiations in Copenhagen (Van der Sluijs et al. 2010), defeat of a 7-yr effort in the U.S. Senate to pass a climate bill centered on cap and trade, increase in prominence of skeptics in the news media, and the formation of an InterAcademy Independent Review of the IPCC.

The monster is too big to hide, exorcise, or simplify. Increasing concern that scientific dissent is underexposed by the IPCC's consensus approach argues for ascendancy of the monster detection and adaptation approaches. The challenge is to open the scientific debate to a broader range of issues and a plurality of viewpoints and for politicians to justify policy choices in a context of an inherently uncertain knowledge base (e.g., Sarewitz 2004). Some ideas for monster taming strategies at the levels of institutions, individual scientists, and communities are presented.

Taming strategies at the institutional level.

The misuse that is made [in politics] of science distorts, politicizes and perverts that same science, and now we not only must indignantly cry when science falters, we also must search our consciences.

—Diederik Samsom

The politics of expertise describes how expert opinions on science and technology are assimilated into the political process (Fischer 1989). A strategy used by climate policy proponents to counter the strategies of the merchants of doubt (Oreskes and Conway 2010; Schneider and Flannery 2009) has been the establishment of a broad international scientific consensus with high confidence levels, strong appeals to the authority of the consensus relative to opposing viewpoints, and exposure of the motives of skeptics. While this strategy might have been arguably useful, needed, or effective at some earlier point in the debate to counter the politically motivated merchants of doubt, these strategies have enraged the uncertainty monster, particularly since the Climategate e-mails and errors that were found in the IPCC AR4 Working Group II (WGII) report (e.g., Van der Sluijs et al. 2010).

Oppenheimer et al. (2007, p.) remark that "the establishment of consensus by the IPCC is no longer as important to governments as a full exploration of uncertainty." The institutions of climate science, such as the IPCC, the professional societies and scientific journals, national funding agencies, and national and international policy-making bodies, have a key role to play in taming the uncertainty monster. Objectives of taming the monster at the institutional level are to improve the environment for dissent in scientific arguments; to make climate science less political, clarify the political values and visions in play; to expand political debate; and to encourage experts in the social sciences, humanities, and engineering to participate in the evaluation of climate science and its institutions. Identifying areas where there are important uncertainties should provide a target for research funding.

Taming strategies for the individual scientist.

Science . . . never solves a problem without creating ten more.

—George Bernard Shaw

Individual scientists can tame the uncertainty monster by clarifying the confusion and ambiguity associated with knowledge versus ignorance and objectivity versus subjectivity. Morgan et al. (2009) argue that doing a good job of characterizing and dealing with uncertainty can never be reduced to a simple cookbook, and that one must always think critically and continually ask questions. Spiegelhalter (2011) provided the following advice at the recent workshop on Handling Uncertainty in Science at the Royal Society:

- We should try and quantify uncertainty where possible
- All useful uncertainty statements require judgment and are contingent
- We need clear language to honestly communicate deeper uncertainties with due humility and without fear
- For public confidence, trust is more important than certainty

Richard Feynman's (1974, p. 11) address on "cargo cult science" clearly articulates the scientist's responsibility: "Details that could throw doubt on your interpretation must be given, if you know them. You must do the best you can—if you know anything at all wrong, or possibly wrong—to explain it. If you make a theory, for example, and advertise it, or put it out, then you must also put down all the facts that disagree with it, as well as those that agree with it . . . In summary, the idea is to try to give *all* of the information to help others to judge the value of your contribution; not just the information that leads to judgment in one particular direction or another."

Impact of integrity on the monster.

He who fights with monsters might take care lest he thereby become a monster.

—Friedrich Nietzsche

Integrity is an issue of particular importance at the science–policy interface, particularly when the scientific case is represented by a consensus that is largely based on expert opinion. Integrity is to the uncertainty monster as garlic is to a vampire.

Gleick (2011) distinguishes a number of tactics that are threats to the integrity of science: appealing to emotions, making personal (ad hominem) attacks, deliberately mischaracterizing an inconvenient argument, inappropriate generalization, misuse of facts and uncertainties, false appeal to authority, hidden value judgments, selectively omitting inconvenient measurement results, and packing advisory boards.

The issue of integrity is substantially more complicated at the science–policy interface, particularly since the subject of climate change has been so highly politicized. A scientist's statement regarding scientific uncertainty can inadvertently become a political statement that is misused by the merchants of doubt for political gain. Navigating this situation is a considerable challenge, as described by Pielke (2007). Individual scientists can inadvertently compromise their scientific integrity for what they perceive to be good motives. Whereas such actions can provide temporary political advantages or temporarily bolster the influence of an individual scientist, the only remedy in the long run is to let the scientific process take its course and deal with uncertainty in an open and honest way.

The hopeful monster.

There are very few monsters who warrant the fear we have of them.

—Andre Gide

The "hopeful monster" is a colloquial term used in evolutionary biology to describe the production of new major evolutionary groups. Here we invoke the hopeful monster metaphor to address the possibility of taming the monster through the evolution of new entities, enabled by social computing.

When the stakes are high and uncertainties are large, Funtowicz and Ravetz (1993) point out that there is a public demand to participate and assess quality, which they refer to as the extended peer community. The extended peer community consists not only of those with traditional institutional accreditation that are creating the technical work but also those with much broader expertise that are capable of doing quality assessment and control on that work.

New information technology and the open knowledge movement are enabling the hopeful monster. These new technologies facilitate the rapid diffusion of information and sharing of expertise, giving hitherto unrealized power to the peer communities. This newfound power has challenged the politics of expertise, and the "radical implications of the blogosphere" (Ravetz 2010) are just beginning to be understood. Climategate illustrated the importance of the blogosphere as an empowerment of the extended peer community, whereby "criticism and a sense of probity were injected into the system by the extended peer community from the (mainly) external blogosphere" (Ravetz 2010).

While the uncertainty monster will undoubtedly evolve and even grow, it can be tamed through understanding and acknowledgement, and we can learn to live with it by adapting our policies to explicitly include uncertainty. Beck et al.'s (2009, p. 59) statement describes a tamed and happy monster: "Being open about uncertainty should be celebrated: in illuminating where our explanations and predictions can be trusted and in proceeding, then, in the cycle of things, to amending their flaws and blemishes."

ACKNOWLEDGMENTS. This paper was motivated by the Royal Society's Workshop on Handling Uncertainty in Science, held in London, 22–23 March 2010. We would like to thank the denizens of the blog Climate Etc. (www.judithcurry.com) who have provided stimulating discussions and also links to useful reference material on several topics discussed in this paper. We would also like to thank the following individuals who provided comments on the paper: Brian Hoskins, Dan Hughes, Mark Jelinek, Tim Palmer, Roger Pielke Sr., William Rossow, Hans von Storch, Paul Baer, and Michael Welland. The anonymous reviewers provided very helpful comments that improved the paper substantially. This research was supported by NOAA through a subcontract from STG (Curry) and Grant NSF-ATM (Webster).

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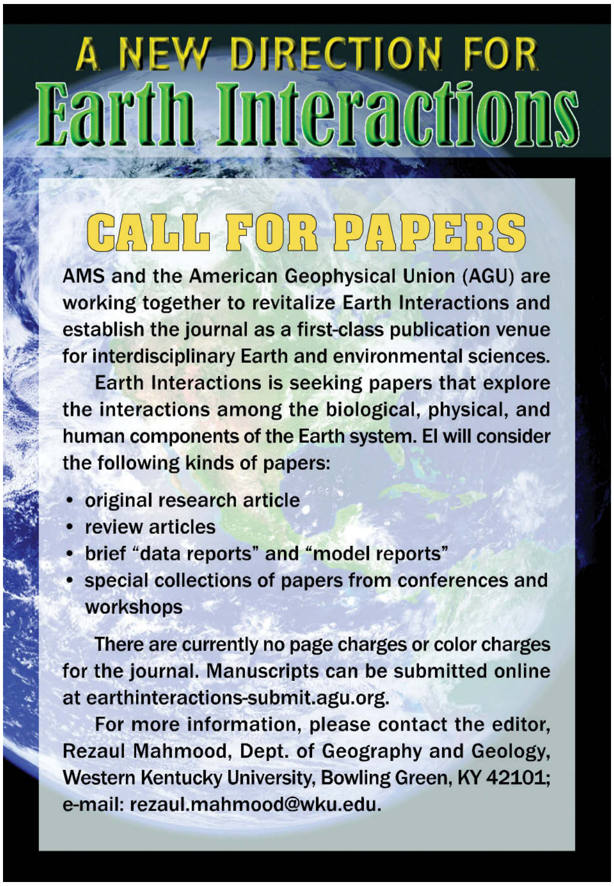

Comment on "Climate Science and the Uncertainty Monster" by J. A. Curry and P. J. Webster

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Curry and Webster (2011) discuss the important topic of uncertainty in climate research. While we agree that it is very important that uncertainty is estimated and communicated appropriately, their discussion of the treatment of uncertainty in the IPCC assessment reports regarding attribution is inaccurate in a number of important respects.

IPCC has placed high priority on communicating uncertainty (Moss and Schneider 2000; Mastrandrea et al. 2010, 2011). Since detection of climate change and attribution of causes deals with distinguishing "signals" or "fingerprints" of climate change from climate variability, an approach requiring substantial use of statistics (see Hegerl et al. 2007), this area of research has always placed high priority on estimating uncertainties appropriately. Hence the chapter on attributing causes to climate change of IPCC AR4 (Hegerl et al. 2007) discusses the uncertainty in its findings in detail, including in an overview table where remaining uncertainties are explicitly listed for each finding. In this brief comment we will limit our focus to the four key errors and misunderstandings in Curry and Webster (2011) regarding the treatment of uncertainty in the detection and attribution chapter of IPCC AR4:

1) The authors claim that "The 20th century aerosol forcing used in most of the AR4 model simulations (Section 9.2.1.2) relies on inverse calculations of optical properties to match climate model simulations with observations" and thus claim "apparent circular reasoning." This is incorrect. The inverse estimates of aerosol forcing given in 9.2.1.2 are derived from observationally based analyses of temperature and are compared in Chapter 9 with "forward" estimates calculated directly from understanding of the emissions in order to determine whether the two are consistent. But it is critical to understand that such inverse estimates are an *output* of attribution analyses not an *input*, and thus the claim of "circular reasoning" is wrong. The aerosol forcing used in 20C3M (see http://www-pcmdi.llnl.gov/projects/cmip/ann_20c3m.php) climate model simulations was based on forward calculations using emission data [Boucher and Pham 2002; see references in Randall et al. (2007)]. Further, detection and attribution methods determine whether model-simulated temporal and spatial patterns of change (referred to as fingerprints) that are expected in response to changes in external forcing are present in observations. For example, the aerosol fingerprint shows a spatial and temporal pattern of near-surface temperature changes that varies between hemispheres and over time (see Hegerl et al. 2007, Section 9.4.1.5). The solar fingerprint shows a vertical pattern of free atmosphere temperature changes that has warming throughout the atmosphere unlike the

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DOI: 10.1175/BAMS-D-11-00191.1

observed pattern of warming in the troposphere and cooling in the stratosphere, and also has a distinct temporal pattern, particularly on longer time scales. These patterns make the response to solar and aerosol forcing distinguishable (with uncertainties) from that due to greenhouse gas forcing. The amplitude of those fingerprint patterns is estimated from observations. Therefore, attribution of the dominant role of greenhouse gases in the warming of the past half-century is not sensitive to the uncertainties in the magnitude of aerosol forcing, or of other forcings, such as solar forcing. If the observed response were (at a given significance level) consistent with a smaller aerosol signal, balanced by a smaller greenhouse gas signal than that used in the models, then the results from fingerprint studies would include these possibilities within their statistical uncertainty ranges. Thus, attribution studies sample the range of possible forcings and responses much more completely than climate models do (Kiehl 2007). Also, the IPCC AR4 assessment carefully explores other possible explanations, such as solar forcing alone, and finds that "it is very likely that greenhouse gases caused more global warming over the last 50 years than changes in solar irradiance," based on studies exploring a range of solar forcing estimates and using a range of data (Section 9.4.1.5, Hegerl et al. 2007). Such studies also attribute the warming in the first half of the twentieth century to a combination of external natural and anthropogenic forcing and internal climate variability (Table 9.4) Thus, Curry and Webster misrepresent the role of forcing magnitude uncertainties in attribution and do not appreciate the level of rigor with which physically plausible alternative explanations of the recent climate change are explored.

2) ". . . no traceable account is given in the AR4 of how the likelihood assessment in the attribution statement was reached": Expert open reviews are designed to ensure that the steps taken during the AR4 were clear to attribution experts. An explanation of how the assessment was obtained is given in the introduction to the chapter, and includes a description of how the overall expert assessment is based on technical results and an assessment of their robustness, downgraded to account for remaining uncertainties (Section 9.1.2, second-to-last paragraph). The detailed assessment of the causes of a variety of observed climate changes, including the results from published studies, the remaining uncertainties, and

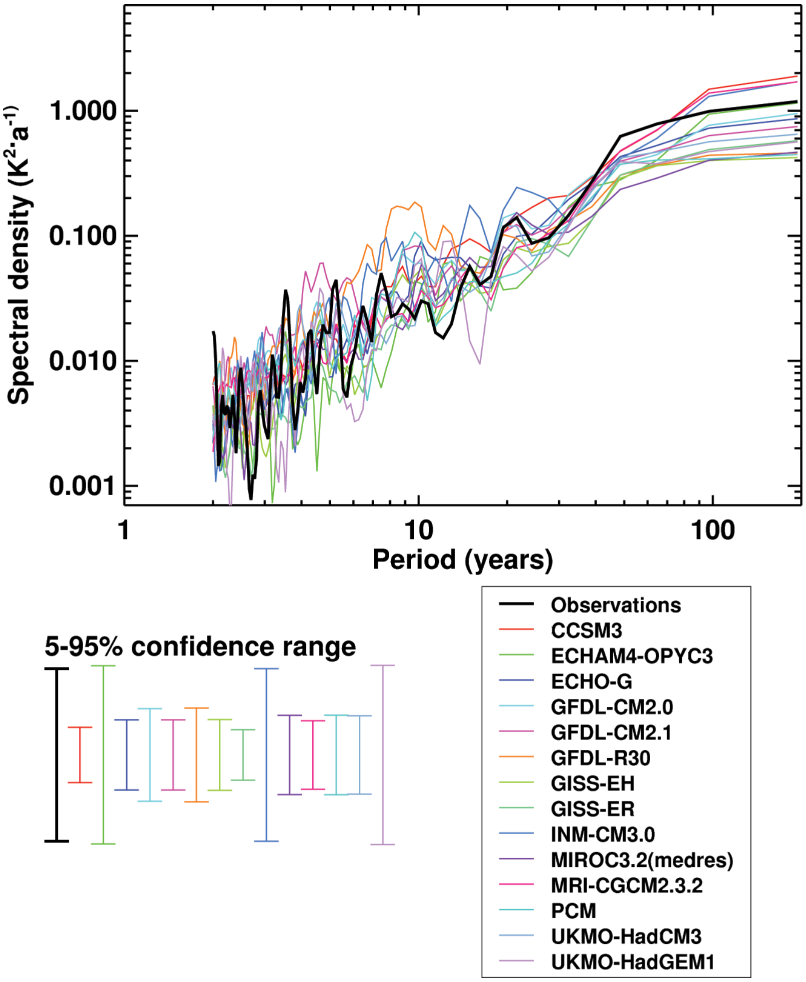

Fig. 1. Comparison of variability as a function of time scale of annual global mean temperature from observations (black) and multiple model simulations of the twentieth century [colors; for details see Fig. 9.7 of Hegerl et al. (2007)]. This figure is used by the authors to claim that "the power spectra of observed and modeled global mean temperatures in figure 9.4 of the IPCC AR4 shows that all models underestimate the amplitude of variability on periods of 40–70 years." Note the uncertainty in the observed and simulated spectral estimates (vertical bars).

the overall assessment is given in Table 9.4, which extends over more than 3 printed pages. However, improving the communication of such material to the broader audience of scientists who are not directly involved in attribution studies is also an important goal, and this exchange shows this can be improved.

3) "The high likelihood of the imprecise "most" seems rather meaningless": We disagree. The likelihood describes the assessed probability that "most" (i.e., more than 50%), of the warming is due to the increase in greenhouse gases. This statement has a clear meaning and an associated uncertainty, although explicitly listing ">50%" in the text to ensure that no misunderstandings are possible could be helpful in future work.
4) The authors claim that "Fig. 9.4 of the IPCC AR4 shows that all models underestimate the amplitude of variability of periods of 40–70 years." This is an incorrect conclusion because Curry and Webster do not appear to have considered the uncertainties that were presented in the chapter. The figure (Fig. 9.7, not Fig. 9.4 of the assessment) clearly shows that the simulated variability of annual global mean temperature on time scales of 40–70 years is consistent with the variability estimated from observations, given uncertainty in spectral estimates. Detection and attribution methods account for the contribution by internal climate variability to observed climate changes. Since the estimates of climate variability that are used for this purpose are generally obtained from climate model data, the chapter also contains a detailed discussion of the reliability of climate model variability for detection and attribution. Section 9.4.1.3 states that detection and attribution methods yield an estimate of the internally generated climate variability in observations and palaeoclimatic reconstructions (see Section 9.3.4) that is not explained by forcing. This "residual" is comparable to the variability generated by climate models, and the patterns of variability in models reproduce modes of climate variability that are observed (see chapter 8). The remaining uncertainty in our estimates of internal climate variability is discussed as one of the reasons the overall assessment has larger uncertainty than individual studies (see, e.g. Table 9.4).

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Reply

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We would like to thank the authors of the comment (Hegerl et al. 2011), all of whom have played leadership roles in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), for their interest in our paper (Curry and Webster 2011). The authors are correct that since the Third Assessment Report, the IPCC has placed a high priority on communicating their conclusions about uncertainty. Our paper raises the issue of how the IPCC nonetheless again, in the AR4, fell short in this priority as well as in investigating and judging uncertainty. Hegerl et al. focus on the section in our paper on "Uncertainty in the attribution of twentieth-century climate change," which addresses the IPCC AR4 conclusion regarding attribution: "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." (IPCC 2007, p. 10)

We are encouraged that Hegerl et al. (2011) acknowledge the importance of improving traceability—a recommendation made by the InterAcademy Council (IAC 2010) as well. We believe an independent person or group—and not just members of the small community of attribution experts—should be able to understand how the result came to be and to walk through the decision process and achieve the same result. The IPCC should consult with the larger scientific and engineering community experienced in traceability standards to determine what is meant by the IPCC's traceability guidelines, and what kind of traceability is actually suitable for the IPCC assessments. Beyond the quote we provided in our article, the IAC review provides a starting point for a description of what is suitable: ". . . it is unclear whose judgments are reflected in the ratings that appear in the Fourth Assessment Report or how the judgments were determined. How exactly a consensus was reached regarding subjective probability distributions needs to be documented." (IAC 2010; p. 39)

Some fields (e.g., medical science, computer science, engineering) have stringent traceability requirements, particularly for products and processes that are mission critical or have life-and-death implications. We expect the level and type of traceability required of the IPCC will be related to the complexity of the subject matter and the criticality of the final product. Increasing traceability in its assessment reports will enhance both accountability and openness of the IPCC.

Hegerl et al. (2011) state, "The remaining uncertainty in our estimates of internal climate variability is discussed as one of the reasons the overall assessment has larger uncertainty than individual studies." Translating this uncertainty in internal climate variability (among the many other sources of uncertainty) into a "very likely" likelihood assessment is exactly what was not transparent or traceable in the AR4 attribution statement. We most definitely "do not appreciate the level of rigor with which physically plausible non-greenhouse gas explanations of the recent climate change are explored," (Hegerl et al. 2011), for reasons that were presented in our paper. In our judgment, the types of analyses referred to and the design of the Coupled Model Intercomparison Project phase 3 (CMIP3) climate model experiments that contributed to the AR4 do not support a high level of confidence in the attribution.

Hegerl et al. (2011) take issue with our statement that "the high likelihood of the imprecise 'most' seems rather meaningless." Hegerl et al.'s proposal to add ">50%" to the attribution statement might have improved communication of uncertainty on this point. Nonetheless, this small change would still fall short of addressing the problems our article described (and quoted from assessment users) about the fundamental difference between 51% and 99% attribution.

Hegerl et al. (2011) object to our statement in the original manuscript: "Figure 9.7 of the IPCC AR4 shows that all models underestimate the amplitude of variability of periods of 40–70 years," on the basis that we do not consider the uncertainties presented in the chapter. Figure 9.7 is presented on a log–log scale, and the magnitudes of the uncertainties for both the model simulations and the observations are approximately a decade (a factor of 10). Considering uncertainty, a more accurate statement of our contention would have been: The large uncertainties in both the observations and model simulations of the spectral amplitude of natural variability precludes

DOI:10.1175/BAMS-D-11-00195.1

a confident detection of anthropogenically forced climate change against the background of natural internal climate variability.

ACKNOWLEDGMENTS. Comments from the Denizens of Climate Etc. at judithcurry.com are greatly appreciated. Particular thanks to Steve Mosher, John Carpenter, and Pekka Perila on traceability.

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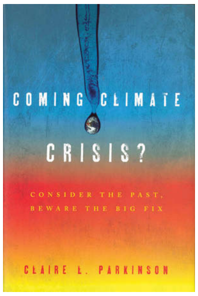
COMING CLIMATE CRISIS? CONSIDER THE PAST, BEWARE THE BIG FIX

Claire L. Parkinson, 2010, 432 pp., $24.95, hardbound, Rowman & Littlefield, ISBN 978-0-7425-5615-7

When I began to read *Coming Climate Crisis?*, by Claire L. Parkinson, I was not expecting to learn much from it. After all, I am a full-time scientist studying the climate and its changes. However, I was pleasantly surprised by the breadth of the areas it covers and captivated by the detailed descriptions of many examples of past attempts by humans to manipulate the weather and climate. It was refreshing for me to read the author's account of the major components and processes of the climate system, and Earth's 4.6 billion years of evolution and climate change, even though I had formal training in these areas in graduate school. After those discussions, the author then provides examples of how human beings have been changing local environments and Earth's climate throughout their existence. These chapters provide a good background and context for the reader to understand the climate change we are currently facing. Most readers will benefit from reading these chapters because even climate scientists work on only a small fraction of the Earth climate system, and these chapters present a full—albeit abbreviated—view of Earth's climate and the role of human activities.

On current global warming, the author details the many adverse impacts of global warming studied in the literature. Most of the materials presented are in agreement with the mainstream view of the climate community that 1) the climate is warming and will likely warm up rapidly in the coming decades, which will be very disruptive to our society and global ecosystems; 2) the main cause for the rapid warming is the increases in atmospheric content of greenhouse gases resulting from human activities; and 3) the negative impacts of global warming greatly outweigh the positive aspects. Nevertheless, the author also provides a fairly detailed account of the issues that a very small fraction of climate scientists (the so-called climate skeptics) have with global warming. I felt that the author unfortunately gave more credit to that handful of skeptics than to mainstream climate scientists.

As the book's focus is on the potential upcoming climate crisis, the author devotes large portions to discussing recently proposed geoengineering solutions to combat global warming, and their potential unintended consequences. Through detailed accounts of past examples of unsuccessful efforts to manipulate local weather and climate—such as cloud seeding, hail suppression, and taming hurricanes—the author presents a very cautious view on any such global-scale human interventions. These past actions were all started with good intentions, but many of them often led to unintended adverse consequences. To combat global warming, any geoengineering attempts would have to be orders of magnitude larger and much more complex than any past efforts, and they will be further complicated by many other political and ethical issues. As our ability to foresee the full impacts of such actions is very limited, most climate scientists would agree with the author's cautious view on this topic (for more discussions on this subject, see Eli Kintisch's book, *Hack the Planet: Science's Best Hope—or Worst Nightmare—for Averting Climate Catastrophe*). Instead, the author promotes many mitigation actions that could be taken by individuals and institutions to reduce emissions of greenhouse gases and thus help slow down global warming.



Although written by a climate scientist—in contrast to other similar books written by nonscientists—the book is quite easy for the general public to read and understand, in part due to the author's fascinating accounts of many past stories and examples. The author's excellent understanding of the climate system and current climate issues comes through strongly. She has done a comprehensive search of the literature, as shown in the many well-referenced examples and numbers. Although the book does not contain any graphics or illustrations, it does provide many numbers that give the reader information to aid comprehension. Nevertheless, I thought that inclusion of some diagrams and illustrations would have better helped describe some of the processes and issues.

Overall, this is a good book written by a climate scientist using easy-to-understand language, with in-depth discussions and broad coverage of the climate issues that are facing our society today. It is well worth reading for anyone who is interested in or concerned about our climate.

—Aiguo Dai

Aiguo Dai has been a climate scientist at the National Center for Atmospheric Research for the last 15 years, studying climate variations and changes with a focus on the hydrological cycle and global and continental scales. He currently chairs the AMS Committee on Climate Variability and Change, and serves as an editor of the Journal of Climate *and as an associate editor of the* Journal of Hydrology.

FOR FURTHER READING

Kintisch, E., 2010: *Hack the Planet: Science's Best Hope—or Worst Nightmare—for Averting Climate Catastrophe*. Wiley, 279 pp.

SEVENTY YEARS OF EXPLORATION IN OCEANOGRAPHY: A PROLONGED WEEKEND DISCUSSION WITH WALTER MUNK

Hans von Storch and Klaus Hasselmann, 2010, 190 pp., $129.00, hardbound, Springer, ISBN 978-3-642-12086-2

As implied by the title, this book is not intended as a textbook (though it may be of academic use to science historians or sociologists). It is, rather, a joyful romp through the history of oceanography that will appeal to both those in the field and those curious about it—touching not just on oceanography, but Earth sciences in general. A fun takeaway message from the book comes in the form of two guiding principles: "keep it simple" and "make it fun." Following these guidelines buoys not only Walter Munk's own enthusiasm (which seems boundless), but also that of anyone nearby (and, incidentally, leads pretty consistently to good science).

Written in the style of an informal discussion between Walter Munk, Klaus Hasselmann, and Hans von Storch, the narrative covers the great sweep of time over which Walter has been a major

NEW PUBLICATIONS

CLIMATE SAVVY: ADAPTING CONSERVATION AND RESOURCE MANAGEMENT TO A CHANGING WORLD

L. J. Hansen and J. R. Hoffman, 2010, 350 pp., $40.00, paperbound, Island Press, ISBN 978-1-59726-686-4

This title considers the implications of climate change for key resource management issues of our time—invasive species, corridors and connectivity, ecological restoration, pollution, and many others. How will strategies need to change to facilitate adaptation to a new climate regime and promote resilience? The book offers a wide-ranging exploration of how scientists, managers, and policy makers can use the challenge of climate change as an opportunity to build a more holistic and effective philosophy.

ENCYCLOPEDIA OF CLIMATE AND WEATHER (SECOND EDITION)

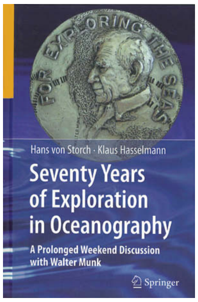
S. H. Schneider and T. L. Root, Eds.-in-Chief, 2011, 1,344 pp., $450.00, hardbound, Oxford University Press, ISBN 978-0-19-976532-4

This volume contains more than 330 entries, covering topics such as the processes that produce weather, the circulation of the atmosphere that produces the world's climates, classification of climates, the history of the atmospheric sciences, and significant weather events. This edition includes new articles on such subjects as the Kyoto Protocol, global warming, tradable permits, and extreme weather. Each entry is fully cross-referenced to both definitions of weather- and climate-related terms as well as additional sources for further study.

THE THOUSAND-YEAR FLOOD: THE OHIO–MISSISSIPPI DISASTER OF 1937

D. Welky, 2011, 384 pp., $27.50, hardbound, University of Chicago Press, ISBN 978-0-226-88716-6

This is the first comprehensive history of one of the most destructive disasters in American history: flooding in the Midwest that killed nearly 400 people and caused more than $500 billion of damage at a time when the Great Depression still battered the nation. The book first shows how decades of settlement put Ohio valley farms and towns at risk and how politicians and planners repeatedly ignored the dangers. Then it tells the story of the disaster itself and the people affected by it, as well as of the rebuilding of communities in the flood's aftermath.



influence in the field: roughly from 1940 to this very day. From predicting the waves for D-Day and monitoring tidal waves from the nuclear tests in the Pacific, on through tides, internal waves, general circulation (both wind-driven and abyssal), and ocean acoustics, there are few oceanographic specialties that do not have the name Munk written large (and often) on them. Yet the intimate tone and broad scope of the subject matter complement each other nicely, leaving the reader with a feeling of really getting to know this remarkable man, and the extraordinary life he has led. Time and again, Walter Munk has leapt into a new discipline, working hard to pick up new approaches and overcoming most difficulties with his infectious enthusiasm, then bringing new results back to the Earth sciences (and often bolstering progress in the associated "other" fields as well). A good example (and but one of very many) is his work on tides: since the astronomical forcing was identified (very long ago—as far back as Aristotle, at least), tidal predictions were essentially considered "solved." But "noise" arising from other forcing (wind, pressure) can in some places and times overwhelm the astronomical tides. Walter's approach, incorporating noise explicitly, permits objective determination of which of the tidal frequencies arising from the Sun + moon + Earth system are "significant" (i.e., are worth determining). The importance of this approach is discussed in a section with perhaps the book's most striking title: "The Alleged Suicide of Aristotle." Aristotle, it is alleged, tried to predict the tidal currents through the Strait of Euripus. To quote Walter: "there is a widespread story that when he failed he threw himself into the turbulent rapids." As it turns out, the tides in this strait fade away almost completely during the neap part of the spring-neap cycle, leaving only the other dynamically forced currents (mainly due to winds and atmospheric pressure systems, which are much harder to predict!). So Aristotle could have benefitted from such a "noise analysis." Rather than the traditional method of using harmonic analysis to empirically determine the strength of each tidal "constituent" (frequency component) at each location, Walter wanted to model the motion of the ocean due to the known tidal forcing (and with known basin geometry and bathymetry), so predictions could be made anywhere, without having to gather weeks and weeks of data for each new location. Of course, the solid Earth tides and

BREAKING AND DISSIPATION OF OCEAN SURFACE WAVES

A. Babanin, 2011, 463 pp., $130.00, hardbound, Cambridge University Press, ISBN 978-1-107-00158-9

This book outlines the state-of-the-art in the understanding of wave breaking and presents the main outstanding problems. It describes analytical and modeling approaches to the study of wave breaking and dissipation; proposes means and approaches to parameterize dissipation terms for wave-forecast models, which will be of importance for wave forecasters and meteorological centers; and provides a review of the wave-breaking roles and feedbacks in the atmospheric boundary layer and upper ocean.

CLIMATE CHANGE POLICIES: GLOBAL CHALLENGES AND FUTURE PROSPECTS

E. Cerdá and X. Labandeira, Eds., 2010, 284 pp., $115.00, hardbound, Edward Elgar, ISBN 978-1-84980-828-6

This title sheds light on the foundations, design, and effects of climate change policies. It deals with the various economic effects from climate change policies introduced at national and international levels, and it also describes actual applications of climate change policies in the main emitting countries. It includes chapters on public policies and climate change impacts, adaptation, mitigation, effects on competitiveness, new technologies, distributional concerns, and the international dimension.

VIRTUAL WATER: TACKLING THE THREAT TO OUR PLANET'S MOST PRECIOUS RESOURCE

T. Allan, 2011, 368 pp., $18.00, paperbound, I. B. Tauris, ISBN 978-1-84511-984-3

The virtual water concept—created by the author of this book—determines the amount of water used to produce goods and services, including manufacturing, packaging, and transportation. This title exposes the real impact of our modern lifestyle on the world's water supplies and shows how we as individuals, and governments globally, can make a vital contribution to managing our water use in a more sustainable and planet-friendly way.

many other factors have to be figured in for this to work. Modern tidal models for the whole Earth are finally getting pretty close.

For those familiar with the field, it may be fun to play the game, "How many of the people mentioned do I know?" For others, it is little trouble to skip the few lists of names. In any case, the grand sense of perspective on the development of oceanography—and on the development of our post-World War II science programs in general—are well worth the journey.

So my recommendation is: Go ahead, get to know Walter. You'll be glad you did.

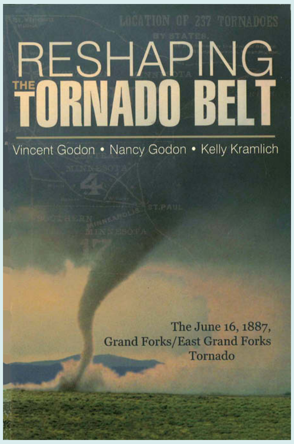
—Jerome A. Smith

Jerome A Smith is a researcher in physical oceanography at Scripps Institution of Oceanography, and an editor for the Journal of Physical Oceanography.

BOOK EXCERPT

The following passage is excerpted from *Reshaping the Tornado Belt: The June 16, 1887, Grand Forks/East Grand Forks Tornado*, pages 244–251, by Vincent Godon, Nancy Godon, and Kelly Kramlich (2011, iUniverse.com, 408 pp., paperbound, $25.95, ISBN 978-1450244282). Copyright © 2011 by Vincent Godon, Nancy Godon, and Kelly Kramlich. Used by permission.

The main question in the days following June 16, 1887, was what exactly had hit the Grand Forks/East Grand Forks area. There was not a single report in any newspaper that a distinctive wedge-shaped tornado was visually observed by anyone along the twenty-mile-long damage path. If someone had actually seen a wedge-shaped tornado extending from the cloud base to the ground, it would have eliminated some of the confusion. Since this did not happen, newspaper accounts called the event a variety of things.



The *Grand Forks Herald* wrote: "We have read about cyclones and of the terrible devastation they cause. But today we had an awful realization of their destructive power." [John Park] Finley himself described a cyclone as "not a tornado" but a storm that initiates in the West Indies and travels in a parabolic curve along the Atlantic coast. Finley went on to say: "At the immediate center of the storm (cyclone) there is a dead calm." From these two descriptions, it is clear Finley's early definition of a cyclone is what is now termed a hurricane.

Another headline in the *Grand Forks Herald* read: "A Terrible Hurricane Sweeps Over the Country and City." Finley termed a hurricane as "a straight wind of extraordinary velocity," the duration of which may be "a few minutes or for several hours." The Signal Service's official wind speed scale classified wind speeds of eighty mph or greater as "hurricane" winds. Since the official MWS station at the St. Paul, Minneapolis and Manitoba freight depot in Grand Forks had measured wind speeds of eighty mph before the gauge was broken, it did meet the Signal Service's definition of hurricane strength winds. However, in today's terms, a high-wind event in North Dakota would not be called a "hurricane" but rather a "straight-line" or a "downburst wind" event.

The *Larimore Pioneer* declared: "A terrible tornado visited Grand Forks this afternoon doing vast damage to life and property." Finley's definition of a tornado was "a funnel-shaped cloud," which rotated around a vertical axis "As you would turn a nut onto a bolt, point downward" (cyclonic or counter-clockwise). A tornado also had "an immensity of power almost beyond calculation." This definition stands true even today.

Finally, a Jamestown, Dakota Territory, newspaper noted: "The storm at Grand Forks was bad enough but not as disastrous as at first thought. It seemed to be more of a whirlwind than a cyclone, without the irresistible column that goes along with the latter phenomenon." A whirlwind was defined by Finley as an event that will "suddenly start up from some barren, sandy spot unduly exposed to the direct rays of the sun." He also considered a whirlwind to be "harmless and generally of a few moments' duration." Again, this Finley definition also matches today's version. Another common term for a whirlwind today would be a dust devil.

The *Grafton News and Times* expressed what many confused people probably also thought: "It may be in the form of a cyclone, a tornado, a whirlwind or a hurricane but it matters not what it may be called, its effects are to be dreaded." The official designation came from the weather experts in the Signal Service. In the days following the Grand Forks/East Grand Forks tornado, the *Grand Forks Weekly Plaindealer* ran a follow up story about the event. In the article, it wrote "The United States signal service have officially announced that Grand Forks is at least a hundred miles north of the cyclone (tornado) belt." Because of this fact, it was stated the storm "was no more of a cyclone than an ox is a race horse, neither was it a tornado. The terms cyclone and tornado are the names of circling winds." This announcement did not come from the nearby Moorhead or St. Vincent Signal Service offices but rather from the Signal Service headquarters in Washington, which wanted to set the record straight. To accomplish this, the Signal Service sent a graphic to Grand Forks that depicted the northern limit of the tornado belt. This graphic was printed in the *Grand Forks Weekly Plaindealer*, along with the following explanation: "In order that the home of the tornado and cyclone may be definitely located in the minds of our readers, we publish this morning, an official map of the United States signal service at Washington, showing the tornado and cyclone belt."

It seemed as if the Signal Service put more effort into reinforcing its tornado belt theory than to investigate the clues remaining from the storm. The Signal Service did not even bother to mention it could not have been a tornado for other obvious reasons, like the fact that no rotating cone-shaped cloud was ever seen in contact with the ground. All it came down to was that the event did not fit into their official "map," so the Signal Service officially concluded the storm was a hurricane. The Signal Service stated: "The storm in this (Grand Forks) was a straight wind coming from the northwest, that traveled rapidly enough to be properly denominated a hurricane." Again, at the time, the Signal Service considered a hurricane as a straight line wind of at least eighty mph, not the hurricane thought of today. The Signal Service went on to say: "Hurricanes of such velocity as the one that visited Grand Forks last Thursday are of extremely rare occurrence and are incomparably less destructive than tornadoes or cyclones."

. . .

Even though the Signal Service proclaimed the event was not a tornado, they never sent anyone to look at the evidence. Even if they had, it is unknown what they would have concluded. However, looking at the event today, there are clearly enough indicators to determine this was a tornado. After scouring through the newspaper accounts of the tornado damage, there are several traceable pieces of debris showing various wind directions, which would rule out a straight-line wind event.

. . .

In addition to some of the physical evidence, many descriptions of building and tree damage included the word "twisted." As an example, "W. Franklin's house was badly twisted out of shape, destroying furniture and doing a good deal of damage." Another newspaper description talked specifically about the tree damage: "In a confused mass trees lie strewn in every direction. Strong elms are twisted in every shape, and trees two and three feet deep are uprooted." There was also evidence of the strength of the wind speeds, which could not have been made by straight-line winds alone: "A small piece of wood, four or five inches long and half an inch thick is driven into solid elm so that it cannot be pulled out. Boards are scattered around that must have blown a mile at least." Sightseers also found "a piece of inch pine board that had been driven though another pine board two inches thick." At the Grand Forks fairgrounds, there was more evidence of tornadic winds. "All over the grounds pieces of lumber are sticking up, having been driven one and two feet into the earth." The *Grand Forks Weekly Plaindealer* also made the comment: "The fences and sheds at the fairgrounds were blown down and whisked about in every direction."

Putting these pieces of information together, it was concluded a tornado did hit the Grand Forks/East Grand Forks area. The authors believe that the tornado was hidden from view. Since the event occurred in the middle of the afternoon in a fairly large-sized town, it should have been seen if it was not masked by something. Tall trees or terrain could not have blocked the view, as the Grand Forks/East Grand Forks area was located in a flat ancient lakebed with few large trees. Therefore, it was likely rain-wrapped or hidden by blowing dirt, dust, and debris. Furthermore, the Grand Forks/East Grand Forks tornado was also part of a larger scale convective event, as many areas from south of Jamestown, Dakota territory, to near Crookston, Minnesota, also experienced hail, strong winds, or tornadoes. Therefore, the Grand Forks/East Grand Forks tornado could have been part of a much larger scale derecho event, which is a long-lived straight-line wind event. Within a derecho, small-scale bow echoes can be produced. Under the right meteorological circumstances, swirling vortices can develop on either end of these bow echoes, and can produce tornadoes. However, without modern-day meteorological tools, how the storm complex evolved between Dickey County, Dakota Territory, and Polk County, Minnesota, remains a mystery.

AMS BOOKS

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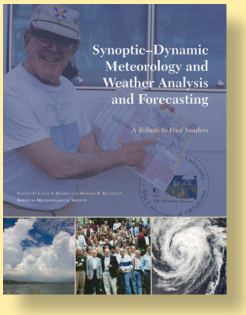

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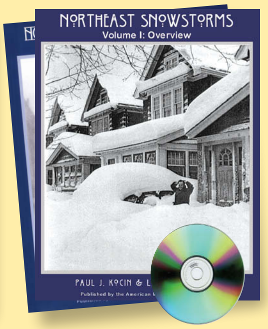

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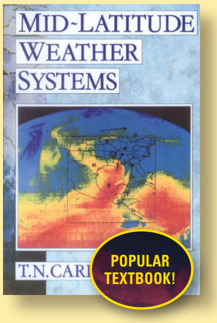

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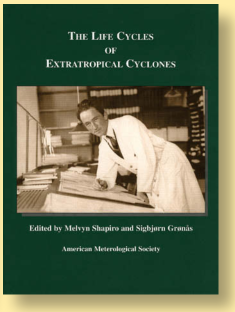

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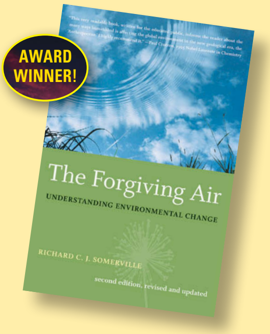

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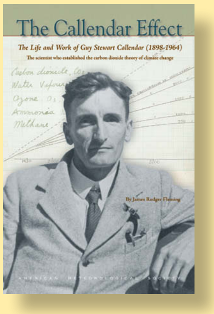

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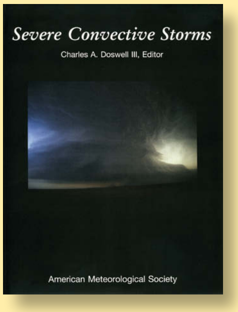

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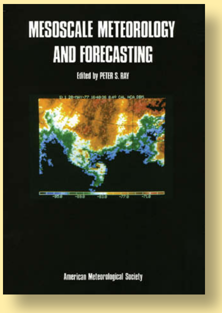

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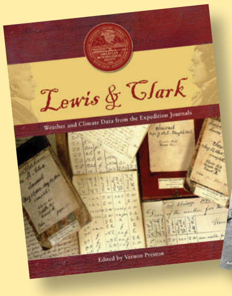

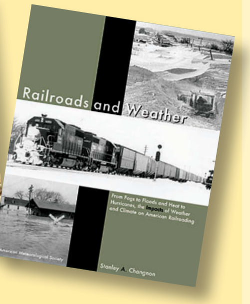

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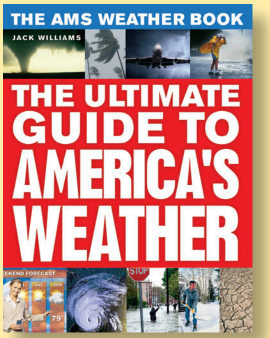

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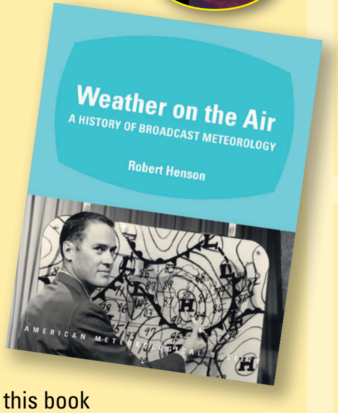

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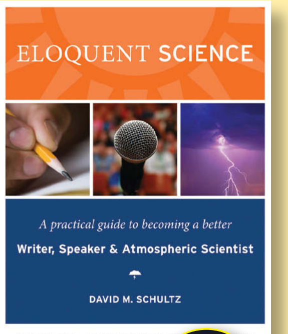

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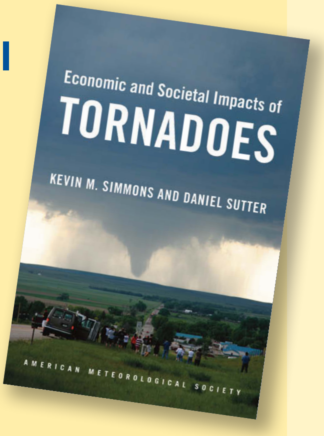

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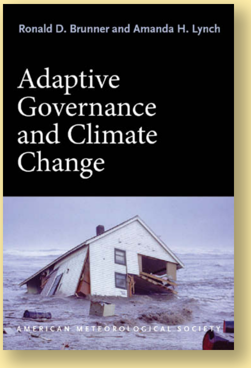
Adaptive Governance and Climate Change

RONALD D. BRUNNER AND AMANDA H. LYNCH



Brunner and Lynch recommend opening the international climate change regime to the complementary approach of adaptive governance—an approach that has succeeded in some local communities and can be under-taken by others around the globe. Features a political and historical analysis of climate change policy, and shows how adaptive governance has worked on the ground in Barrow, Alaska, and other communities.

©2010, PAPERBACK, 424 PAGES, ISBN 978-1-878220-97-4, AMS CODE: AGCC
LIST $35 MEMBER $22

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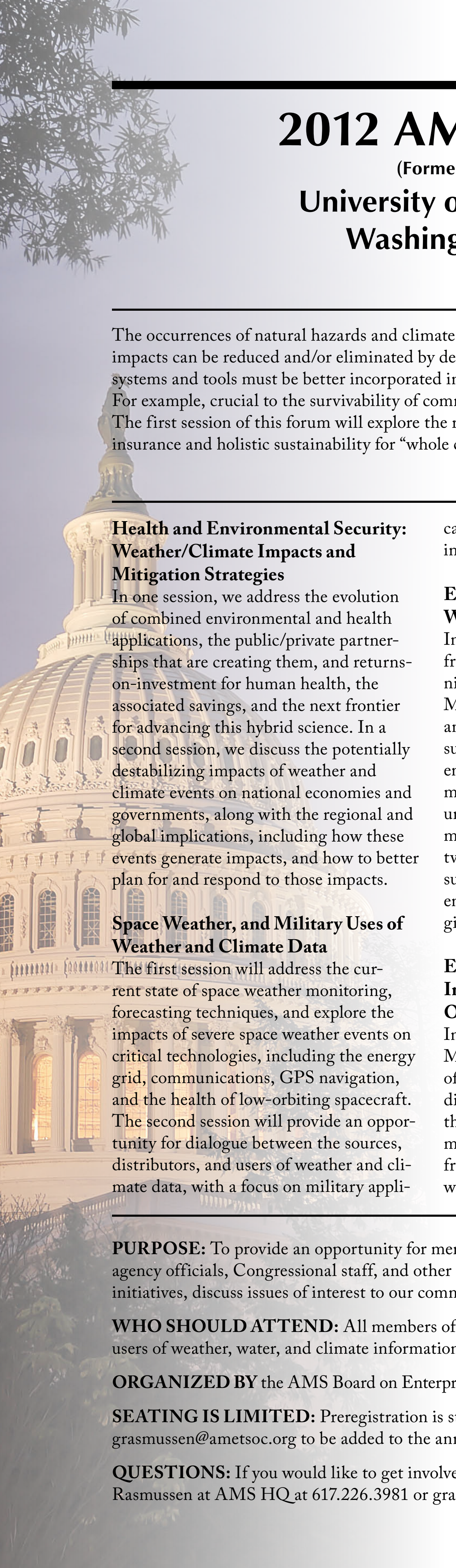


2012 AMS Washington Forum

(Formerly the Public–Private Partnership Forum)

University of California—Washington Center
Washington, D.C. • 10–12 April 2012

FORUM THEME

The occurrences of natural hazards and climate change are inevitable and unavoidable, but their destructive financial and emotional impacts can be reduced and/or eliminated by deploying "hazard mitigation and climate adaptation" strategies. Decision support systems and tools must be better incorporated into preparedness paradigms at multiple scales (communities, nations, and regions). For example, crucial to the survivability of communities is their use of catastrophic risk management insurance to protect their assets. The first session of this forum will explore the relationship between hazard mitigation/climate adaptation strategies, risk management insurance and holistic sustainability for "whole community resiliency" to hazards and changes in Weather, Water and Climate.

SESSION TOPICS

Health and Environmental Security: Weather/Climate Impacts and Mitigation Strategies

In one session, we address the evolution of combined environmental and health applications, the public/private partnerships that are creating them, and returns-on-investment for human health, the associated savings, and the next frontier for advancing this hybrid science. In a second session, we discuss the potentially destabilizing impacts of weather and climate events on national economies and governments, along with the regional and global implications, including how these events generate impacts, and how to better plan for and respond to those impacts.

Space Weather, and Military Uses of Weather and Climate Data

The first session will address the current state of space weather monitoring, forecasting techniques, and explore the impacts of severe space weather events on critical technologies, including the energy grid, communications, GPS navigation, and the health of low-orbiting spacecraft. The second session will provide an opportunity for dialogue between the sources, distributors, and users of weather and climate data, with a focus on military applications, including "boots on the ground" insight from real-world situations.

Economic Benefits and Bankability of Weather and Climate Data

In this session, we continue discussions from the 2011 AMS Summer Community Meeting and the 2012 AMS Annual Meeting on gauging the value of weather and climate services and products in areas such as water, transportation, renewable energy, health, and emergency management. We will aim to bridge the gap in understanding of what "bankable data" means in the renewable energy industry to two different communities: insurers, reinsurers, and financiers; and scientists and engineers. The goal is to facilitate synergies for moving the industry forward.

Executive Branch and Agency Initiatives, Plans, Progress and Opportunities

In one session, staff from the Office of Management and Budget and the Office of Science and Technology Policy will discuss programs and pending legislation that may provide opportunities for AMS members. In another session, senior staff from NOAA, NASA, DOE, and FAA will look ahead and provide updates on current meteorological, climatological, and oceanographic programs and provide insights on new science initiatives and directions.

Science and Congress, and International Perspectives on Global Climate Change

The first session explores how to better frame the debate in political circles about the nature of science. For example, how do we increase awareness about science's role as one of the fuels for the growth engine of our economy? In the second session, leading climate scientists from a few different nations will discuss how to promote dialogue and cooperation in anticipation of the upcoming attempt to build a new climate accord in Rio de Janiero in December 2012.

Academia: Training the New Workforce

This session examines new programs in areas such as professional meteorology and weather risk management, where universities proactively work with companies and agencies that hire their graduates to configure programs that directly address employers' evolving needs.

PURPOSE: To provide an opportunity for members of the weather, water, and climate community to meet with senior Federal agency officials, Congressional staff, and other community members to hear about the status of current programs, learn about new initiatives, discuss issues of interest to our community, identify business opportunities, and speak out about data and other needs.

WHO SHOULD ATTEND: All members of the weather, water, and climate community are encouraged to attend, as well as end users of weather, water, and climate information.

ORGANIZED BY the AMS Board on Enterprise Economic Development, Commission on the Weather and Climate Enterprise

SEATING IS LIMITED: Preregistration is strongly recommended. Watch the AMS_PSL list for announcements. Send e-mail to grasmussen@ametsoc.org to be added to the announcement list.

QUESTIONS: If you would like to get involved in helping to plan future meetings, or if you have any questions, please contact Gary Rasmussen at AMS HQ at 617.226.3981 or grasmussen@ametsoc.org.

Dealing Honestly with Uncertainties in Our Understanding of Climate Change

Earlier this year, I wrote of trying to neutralize the language associated with global warming (*BAMS*, April 2011, p. 497). At that time, I suggested that I would be using the terms "convinced" and "unconvinced" to describe those who had been convinced by the evidence that anthropogenic climate change was occurring and those who had not been convinced. So far, I have found this terminology pretty easy to incorporate in my writing and speaking, and I find it works pretty well.

Shortly after that column appeared, I received a note from a long-time AMS member who rightly suggested that I had oversimplified the situation. As he noted, there are scientists who are convinced that humans are affecting climate in significant ways but who feel that anthropogenic influences other than the increase in greenhouse gases—such as aerosols, land use changes, etc.—can play a larger role than typically acknowledged. Some scientists studying these other human influences—despite being among those I would refer to as among the "convinced"—find their work discounted, or even marginalized, since their results complicate the simpler picture of increasing greenhouse gases representing the only major anthropogenic forcing term for a changing climate.

Scientists generally welcome any avenue of research that is carried out with integrity and scientific rigor—especially when the results of that research challenge our thinking. It has become harder to maintain that ideal objective stance with respect to the science of climate change because of the politically charged atmosphere that now surrounds the topic. Results that complicate the picture, or that explore more deeply the uncertainties in our knowledge, are quickly seized by some as evidence that the research results on the role of greenhouse gases in the warming of the planet must be wrong. In such a confrontational environment, the discomfort we all feel in the face of uncertainty can make it hard to avoid compromising our scientific objectivity.

In this issue, Judith Curry and Peter Webster present a provocative paper on "uncertainty monsters." Many climate scientists will be angered by this paper, feeling that it undermines the consensus reports and calls their results into question. Many in the unconvinced crowd will hail this paper as justifying their position, and it will probably be widely quoted on the blogs devoted to arguing that anthropogenic global warming does not exist. Neither should be the case. The climate science community should view this as an opportunity to discuss the approaches to uncertainty that have been employed (as also occurs in this issue), but all of us in the scientific community should also appreciate the reminder that our desire to develop a self-consistent and coherent picture sometimes impedes our ability to work toward unraveling the full complexity of the climate system. The unconvinced crowd should see this paper as promoting a standard of scientific honesty that most of their blogs and opinion pieces simply cannot meet.

I have enormous faith in the scientific process, and feel that the discussions generated through challenges such as that provided in the Curry and Webster paper will lead to increased understanding. Because of the policy decisions the world faces given the potential for truly disruptive climate change, climate science is playing out in a very public and politicized arena, and that makes it harder for the scientific process to move forward in a natural way. We can and should be merciless in our condemnation of unscientific noise that seeks to obscure real scientific results, but we must also embrace legitimate science that seeks to increase our understanding even as it complicates the emerging picture of how the climate system works. We all must continue to work toward insuring that we are operating with the very highest levels of openness and honesty in the presentation of our science.

Keith L. Seitter, CCM
Executive Director

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.]*

Universities as Pupae [*Originally posted 8 October 2011 by William Hooke*]

We're told that holometabolous insects experience a metamorphosis comprising four distinct stages: embryo, larva, pupa, and imago. Take *Lepidoptera*. Let's get past the pointy-headed nomenclature and think of the caterpillar building a chrysalis (its pupal stage) and then emerging as a butterfly.

Wow. Our own adolescence offers nothing to compare. The ugly duckling growing up to be a swan? Nowhere close.

But maybe, just maybe, at this moment in history, universities are in a pupal stage.

(Alert! What follows is not fact, not based on evidence. It's a conjecture, a what if? But please read on. See what you make of it.)

This thought came when I perhaps should have been paying a little more attention to, and tracking a bit more closely, an interesting workshop from a few days ago. (The workshop might well have been dedicated to a colleague I admire, who's investigated, and written a little, on current employment prospects for meteorological graduates.) Participants were addressing, inter alia, the development of curricula that would prepare Earth scientists for the jobs of the future at a local level—jobs as, say, emergency managers, or jobs dealing with climate adaptation strategies at a local or city level. Discussion was pretty lively. A couple of evenings earlier, those same folks had heard from Michael Crow, the president of Arizona State University, one of the most thoughtful, articulate university presidents on the national scene.

He'd fired imaginations.

Anyway, listening to the discussion made me wonder, what might the knowledge work of the future look like?

If you've been reading the blog over the past several months, you can guess which way those thoughts headed. The problems we face, the problems that matter—feeding and slaking the thirst of a hungry, parched world, protecting the land, water, air, and ecosystems on which we depend, and hunkering down under the force of nature's extremes—have grown so comprehensive, interconnected, and intractable, as to defy our individual understanding. Even the brightest of us can grasp only the smallest bits and pieces of these challenges. And they're coming fast and furious.

To cope, to live well on the real world, we're going to have to solve our problems as teams. And with today's social networking, and the even greater connectedness likely to come, each of us will be working in small bits. We'll be solving problems as collectives. Our thought process will be more like that of an anthill or beehive. Don't think so? Then why is an upsurge of scholars exploring such concepts (using terminology like swarm intelligence, swarm robotics, hive minds, etc.) and looking for clues about how to analyze work, describe the revolution underway?

Ask yourself, how well are universities preparing students to enter such a work environment?

So much for the output side of universities. Now look at the input side.

Have you heard of Salman Khan and the Khan Academy? No? Chances are good that you will soon. Salman Khan is working with support from Bill and Melinda Gates and others to transform public education, improving quality while making it accessible to all.

Remember your schooling? The teacher taught you in the classroom and you did homework at night.

Now turn that around. Picture yourself watching teacher videos at home, then doing your "homework," your active learning, in the school classroom. Picture you and your fellow students working your homework at individual computers at school.

What's your teacher doing in this new configuration? He/she is monitoring your progress from a console at the desk up front, watching you succeed, watching you get hung up. Get truly stymied? He/she will magically come around, and help you over the rough spot. Then the teacher can turn to identifying, then tutoring the next pupil, while your computer makes sure you've really mastered the new concept. Picture thousands of lectures to choose from. Picture the very best teachers captured on the videos. Picture independent learning as rapid and so long as you're capable, and tailored instruction as needed and not before.

The best part? These aren't just ideas. This is happening. This experiment is underway.

Brilliant.

Now . . . ask yourself: what happens when students who've been taught in this refreshing way reach college? Are they going to be satisfied with the present approach? Or are they going to desire, maybe even demand, something closer to the challenge and freedom of their K–12 experience?

And remember, those thousands of lectures that make up the learning modules will be bite-sized —rather like those demands placed on workers on the other side of college. Maybe in that workplace there'll be a lot of similar just-in-time, zero-inventory learning where workers will see the need to brush up on or master a specific topic or two to meet their needs of the moment, and be in a kind of continual learning mode even as they're working.

And in between these two twenty-first century experiences of learning and the career? A several-century-old master-apprentice guild kind of model for university teaching and graduate work.

But there's a third pressure working on universities.

The escalating cost.

Inflation, demand, the limited supply of the very best classroom opportunities, and the enhanced career opportunities awaiting those graduating from the best schools? They've combined to raise costs for in-state tuition and fees by 35% over the past five years, after accounting for inflation. Costs are rising faster than personal income, consumer prices more generally, and even health insurance.

Even health insurance.

If we agree that the rise in health costs is unsustainable, then surely the trend in costs for higher education can't continue. So, universities are being squeezed . . . by changes in what is being demanded from their graduates, by changes in the education and expectations of the entering students, and by cost pressures.

Squeezed? My first metaphor. Those mental ramblings didn't start out with pupae in mind. But then there was a metamorphosis in my thinking.

Squeezed implies an outside forcing. But really, it has been the success, not any failure, of the (largely) American university over the past six decades that has brought about this world transformation. This pivotal moment is not something that has happened to universities. It's something they've brought about.

Think of the American university as a caterpillar now working on that chrysalis.

And with no more idea than that caterpillar about what will happen next.

Exciting stuff.

A Healthy and Diverse Weather Enterprise Looks to the Future

by Betsy Weatherhead (University of Colorado at boulder)
and George Frederick, CCM (Falcon Consultants LLC)

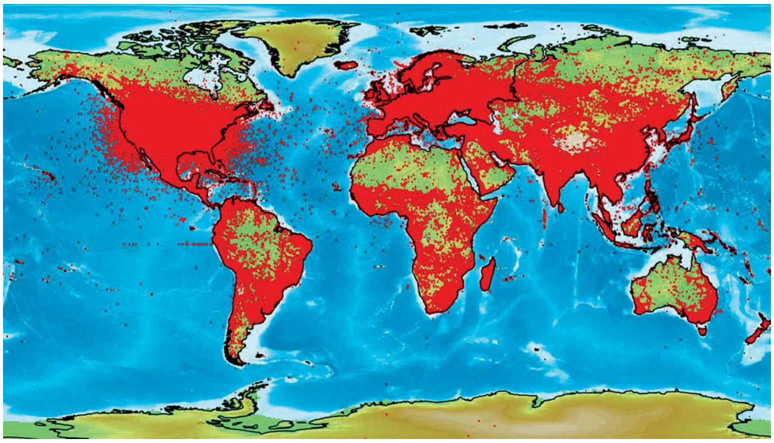
The public, private, and academic sectors involved with providing weather services came together through the AMS and its Commission on the Weather and Climate Enterprise at the 2011 AMS Summer Community Meeting in Boulder, Colorado. More than 200 participants convened to discuss areas of common and pressing interest, with a particular focus this year on the critical data needs and the economic value of meteorological services to society.

The community recognizes that national and global economies have been reeling in recent times from major setbacks from various causes—not the least of which are those created by weather, water, and climate phenomena, from significant tornado outbreaks to the fallout from the tsunami that brought devastation to Japan. The entire weather, water, and climate enterprise has much to offer in recovering and building vibrant global economies. At stake are hundreds of billions of dollars in economic productivity, protection of valuable resources, and the safety of countless lives. Particular areas of interest included

- economic value of the public and private efforts on weather;
- meteorological data;
- transportation;
- renewable energy, with emphasis on offshore wind and solar energy;
- environmental information services;
- carbon and greenhouse gas information products;
- human health; and
- hydrology, with emphasis on drought and floods.

This summary provides an overview of the highlights and crosscutting themes of the meeting, as well as the consensus recommendations from those convened. The meeting provided insight toward the next steps of coordinated, effective action and cooperation across all sectors of the enterprise to address these issues.

Across sectors, a key to the successful use of meteorological information to save lives, protect property, and improve economy is to provide users with information that is tailored to their needs and allows actions to be taken. To this end, a large number of successful companies are using NOAA's fundamental meteorological data and foundational forecasts to provide tailored forecasts to private users. This close and symbiotic relationship is allowing the most effective and efficient delivery of meteorological information in the world. Pivotal to the success of this important industry is continuation of NOAA's ability to provide foundational forecasts. The growth of these private companies, as well as the success of the individuals and industries that rely on the tailored forecasts, requires expanded capabilities to access NOAA's data and weather products to meet the growing demand.



Smart phones made more than a billion weather requests (locations in red) of some U.S. companies during a single day in July 2011, presented by Barry Myers of AccuWeather Inc. at the 2011 Summer Community Meeting. (Image courtesy of the American Weather and Climate Industry Association)

Many of the industries that rely on meteorological information are undergoing transformations that will result in an even stronger reliance on weather information. Automobiles will soon be collecting and sharing a variety of information that can inform others about the safety of road conditions. Increased energy demands and changes to renewable energy will require increasingly precise forecasts within the lowest layers of the atmosphere. Increases in transmittable diseases, as well as skin cancer and asthma, require closer collaboration between health officials and meteorologists to develop effective information for those at risk.

The combined efforts of public, private, and academic sectors are successful and extremely efficient at addressing current needs. As societal demands for more accurate, immediate, and tailored information increase, the coordinated efforts of the enterprise community are likely to be of even greater value. In all likelihood, the transportation, energy, and human health demands for meteorological information will grow in the future, as their needs increase and change. The current model of having NOAA provide foundational data and forecasts while letting private companies meet the needs of individual industries will likely continue to work for most commercial uses of meteorological information. For public health and safety, continued collaboration between government agencies, academia, and private companies will likely address the future requirements.

There is considerable concern across a variety of sectors that rely on meteorological forecasts about a potential gap in satellite coverage in the coming years. There is equal concern about the large cost of satellite development, launch, and maintenance, as well as any cost overruns that may occur. All sectors should be involved in evaluating and prioritizing the large range of options available. The Enterprise is ready to take on this acitivity.

As the economy grows, demands for energy and water will continue. The enterprise is mobilizing to address the future needs, including forecasts relevant to conventional, solar, and wind energies, as well as the increasing estimates of future water resource availability. In many cases, this planning is coordinated at a state or federal level, with direct impact to local municipalities. The fundamental research is ongoing to support these needs, with industry and federal governments becoming increasingly involved in requesting new information for both short-term and long-term planning.

The primary message that pervaded all sessions of this meeting is that the joint efforts of academia, industry, and public sectors are working efficiently and effectively to meet the current needs. While many aspects of society are changing, the demand for reliable and available meteorological information will continue to grow. The ability of the enterprise to meet these demands will have a direct impact on economic health, environmental growth, and appropriate environmental stewardship.

More detailed information about the 2011 AMS Summer Community Meeting is available online at www.ametsoc.org/boardpges/cwce/docs/2011-08/agenda.pdf and http://cires.colorado.edu/science/groups/weatherhead/.

DID YOU KNOW?

- Weather is responsible for roughly 20% of all trucking delays, costing in excess of $3 billion per year. (Dan Krechmer, Cambridge Systematics, Inc.)
- Weather applications are the second-most popular used "apps" on mobile devices—more popular than social networking, maps, music, and news. (Barry Myers, AccuWeather)
- Public Service of Colorado has realized a $3.1M annual savings due to recent improvements in weather forecasts for wind-renewable energy. (Keith Parks, Xcel Energy)
- Forty years ago, the average three-day forecast of hurricane landfall was off by 400 miles; today our average forecast error is almost down to 80 miles. The prospect is real that we will make as much progress in the next 10 years as we have in the past 40. (Alexander E. MacDonald, NOAA)
- Heat waves kill more people than floods, lightning, tornadoes, and hurricanes combined (1995–2004); forecasting and communicating these risks saves lives. (Christopher Uejio, NCAR/CDC)
- The US economic activity (GDP) varies by up to plus-or-minus 1.7% due to weather variability, resulting in impacts as large as $485 billion of the $14.4 trillion 2008 GDP. (Jeff Lazo, NCAR)
- There are 70,000 new cases of potentially deadly skin cancer (melanoma) every year. A new mobile application developed by university scientists helps individuals know when they've been exposed to too much ultraviolet radiation. (Craig Long, NOAA/NWS)

CONWAY B. LEOVY

1933–2011

Conway Barbour Leovy, Professor Emeritus in atmospheric sciences and geophysics at the University of Washington (UW), died of colon cancer at his home in Seattle, Washington, on 9 July 2011. Conway developed an interest in meteorology during his boyhood years growing up in Hermosa Beach, California. After earning his undergraduate degree in physics and mathematics from the University of Southern California in 1954, he enlisted in the U.S. Air Force, where he served as a weather officer stationed in California, Korea, Eniwetok in the Marshall Islands, and Eglin AFB in Florida.

After his discharge from the air force, Conway enrolled in the graduate program in the Department of Meteorology at the Massachusetts Institute of Technology (MIT) and completed his Ph.D. in 1963. His thesis supervisory committee was chaired by Jule Charney. His dissertation—in which he developed an idealized model of the thermally driven, seasonally reversing, pole-to-pole mean meridional circulation of the middle atmosphere—is considered a landmark study and is among his most widely cited works.

Upon graduation from MIT, Conway took a position at the Rand Corporation in Santa Monica, California, where he had the opportunity to deepen his understanding of atmospheric chemistry, boundary layer processes, and large-scale atmospheric dynamics, building blocks for understanding the fundamentals of planetary atmospheres. It was during this time that he began a research collaboration with University of California—Los Angeles (UCLA) professor Yale Mintz, which led to the development of the first general circulation model of the Martian atmosphere.

Correspondence in departmental records indicate that UW had an interest in recruiting Conway as a faculty member dating back to his last year as a graduate student at MIT. However, it was not until 1968 that negotiations proceeded to the point of a formal job offer, which Conway accepted. His UW faculty appointment, which he held until his retirement in 2004, was joint between the Department of Atmospheric Sciences and the Geophysics Program and adjunct with the Astronomy Department. Conway stood out among his faculty colleagues for his remarkable disciplinary breadth: he could be called upon to teach almost any course, and he was highly sought after as a member of thesis supervisory committees and as a problem-solving consultant for students desperately preparing for the departmental qualifying exam. He offered constructive suggestions about innumerable papers by colleagues and students on a wide range of topics. One former student remarked that he was the one faculty member in the department who was truly at home on any of the floors of the Atmospheric Sciences/Geophysics building.

Conway B. Leovy

Conway prepared copious lecture notes for the benefit of the students enrolled in his courses and was well known for his lucid explanations, his challenging and time-consuming homework assignments, and his ability to inspire creativity in the students whose research he supervised. A total of 18 Ph.D. students and 9 M.S. students earned their degrees under his supervision, most of them with financial support from his research grants.

Through their active participation in NASA missions to Venus, Mars, and the outer planets, Conway and his students made many important contributions to our understanding of the circulations of planetary atmospheres, including our own. They found signatures of atmospheric tides and baroclinic waves in the weather records from the *Viking* lander on the surface of Mars. They deduced the existence of strong, seasonally reversing toroidal circulations carrying carbon dioxide from the subliming polar cap in the spring hemisphere to the growing cap in the autumn hemisphere. They showed how the large contrasts in elevation between the Martian highland and lowlands drive strong atmospheric tides, and how the tides in turn contribute to producing episodic global Martian dust storms. They found evidence of an analogue to the equatorial stratospheric quasibiennial oscillation in the equatorial upper atmosphere of Jupiter. They explained how the strong zonal winds at cloud-top level in the atmosphere of Venus, which circulate around the axis of the planet in approximately four Earth days, are in cyclostrophic balance, like tropical cyclones and tornadoes in the Earth's atmosphere. Conway aspired to develop a general theory based on what he viewed as simple scaling considerations that would account for the diverse circulations of planetary atmospheres. Just last year he submitted a paper and gave a departmental seminar presenting his latest thinking on this topic. Conway was a strong supporter of UW's Astrobiology Program, which came into being in the late 1990s. He and astrobiology colleagues have addressed the question of whether a past history of water erosion needs to be invoked to explain the morphology of surface features on Mars.

Throughout much of his career, Conway continued to work on the frontiers of our understanding of the Earth's atmosphere. He and his students used satellite and rocketsonde observations to document the week-to-week and month-to-month evolution of circulation of the middle atmosphere; they discovered a new kind of wave motion with a two-day period at the stratopause level; they showed evidence of the role of planetary wave breaking in the poleward transport of ozone; they estimated the contribution of Kelvin waves to the forcing of the semiannual oscillation at the stratopause level. He was a coauthor (with David Andrews and James Holton) of a highly cited monograph synthesizing these and other results relating to the dynamics of the middle atmosphere. Conway was also fascinated with boundary layer processes. Among the major thrusts of his later research was an effort to better understand the processes that control the extent and morphology of cloud decks in the marine boundary layer.

In recognition of Conway's research achievements, he was designated a Fellow of AMS in 1976 and was the sixth AMS Bernhard Haurwitz Memorial Lecturer in 1999. He was also a Fellow of the American Academy for the Advancement of Science (AAAS) and a corecipient, with other NASA *Viking* investigators, of the AAAS Newcomb Cleveland Award (1978). In 2000, he was awarded the Kuiper Prize of the Division of Planetary Science of the American Astronomical Society. A selected list of his publications and a list of the students who received advanced degrees under his supervision can be found online at www.atmos.washington.edu/people/leovy.

While most of Conway's research was motivated by his innate curiosity about the natural universe, he also felt a strong sense of responsibility to apply his scientific expertise to address important societal problems. In 1983–84, he served as a member of the National Research Council's Committee on the Long Term Atmospheric Effects of Nuclear Weapons. Among the issues considered by the committee was the concern that the lofting of large quantities of smoke into the stratosphere from nuclear explosions might induce an extended interval of cooling and darkening at the Earth's surface—referred to as "nuclear winter." From 1986 to 1989, Conway served as director of the UW's Institute for Environmental Studies, and in that role led the development of curriculum that addressed broad sustainability issues. His last teaching efforts were devoted to large undergraduate courses designed to acquaint students with the science, human, and policy dimensions of global warming. In his free time, Conway worked for many years on projects devoted to educating the public about the risks of nuclear weapons like the ones he had witnessed while on duty on Eniwetok in 1958. He played an active role in administering the Abe Keller Peace Education Fund, which opposes nuclear proliferation and supports peace and social justice. In a 2009 letter published in *Science*, he voiced his concerns about geoengineering as a "fix" for greenhouse warming.

An academic colleague of Conway's who worked with him on social concerns remarked, "Scientists try to contribute to solutions of and public education on important societal problems, but they usually do so within the confines of their fields. Conway also did something more: he actively studied fields outside his own in order to participate in public education in arenas that were not funded, not prestigious, and not always academic.

PUBLICATIONS

AMS REDUCES COLOR CHARGES

Another chunk has been taken out of one of the most significant financial impediments to publishing: the cost of print color figures. It is a long way from a decade ago when the charge for the first color piece was $750. Most recently, the color charge for authors who paid page charges in full was $150 per piece. As of 1 May 2011, AMS has reduced that charge by 40% to $90 per color piece. And we don't intend to stop there. As reduced print runs allow us to increasingly take advantage of reduced color charges afforded by digital printing, additional savings will be passed on to our authors. Many authors have wondered why we can't simply run color in the electronic version of the journals (at essentially no additional cost) while limiting print content to black-and-white; however, that would result in a degraded print product and would be inconsistent with AMS journal quality standards as set by the AMS Council. This latest reduction in color prices reflects our continuing effort to publish visually vibrant journals of the highest quality no matter whether one is reading the print or electronic version.

He was using his gifts to do what many social activists were unable to do. He did so with unfailing respect to everyone and no sense of moral superiority to those with opinions that differed from his own."

Conway played a strategic role in two major conservation projects in the area near his family's cabin in the town of Index on the North Fork of the Skykomish River on the windward side of the Washington Cascades. In the words of Rick McGuire of the North Cascades Conservation Council, "Nobody had ever put significant second-growth forest into wilderness before in Washington state. There were those who were shocked at the idea, but not Conway. He thought it made perfect sense to protect low-elevation forests, even if they weren't old growth, and even if wilderness hadn't been done that way before. And as things turned out, so did Senator Patty Murray, who enjoyed a breakfast at the Leovy's [cabin] one morning before going out to look at those very same forests. And so it came to be that the Wild Sky Wilderness became the first one in Washington state to protect 6,000 acres of second-growth forest, along with 25 miles of salmon streams.

"Around the same time as the Wild Sky effort finished up, a new threat emerged on Heybrook Ridge. If the North Fork Skykomish valley is the back yard of Index, then Heybrook Ridge is its front yard, a low ridge sitting directly south of town . . . unlike Wild Sky, it was on private land, and the owners announced it would be logged unless some way could be found to purchase it. The prospects of saving Heybrook looked hopeless when the people of Index took on the task. Conway got going when things looked grim. With unrelenting effort, and by refusing to give up when there looked to be no possible way to raise enough money, the means were found to protect Heybrook. It stands today, along with the Wild Sky Wilderness, as tribute to those whose efforts saved it, Conway included."

Conway married Janet Lee Seitz in 1958. He is survived by their four children, Joanne, Steven, Jill, and Suzanne; and his seven grandchildren. Throughout their 47-year-long marriage, Conway was devoted to Janet and their children, their numerous pets, and their large extended family. Janet, who worked in the public schools as a reading specialist, died in 2006. In the last four years of his life, Conway enjoyed the close companionship and support of his second wife Carolyn Moloney, who survives him.

Conway was an intrepid hiker whose expeditions took him to the high volcanic peaks and rarely visited thickets and bogs in the Washington Cascades, and the rushing streams that drain the retreating Greenland glaciers. On his hiking expeditions—as in his science and in his life—he eschewed well-worn paths and sought out the frontiers, awed by the grandeur of the world about him and exhilarated by the comradeship of those who traveled with him.

—John M. Wallace

2011 SCIENCE FAIRS

On 12 May 2011, the AMS presented awards to eight high school students participating in the 62nd International Science and Engineering Fair (ISEF) in Los Angeles, California. These awards, ranging from $2,000 to $500, recognized outstanding student work in atmospheric science-related projects.

The Society for Science and the Public's ISEF (sponsored by Intel) is the pinnacle event in a yearlong process of local, regional, state, and national science fairs. More than 1,500 students from the United States, its territories, and 60 additional countries participated in the event held at the Los Angeles Convention Center.

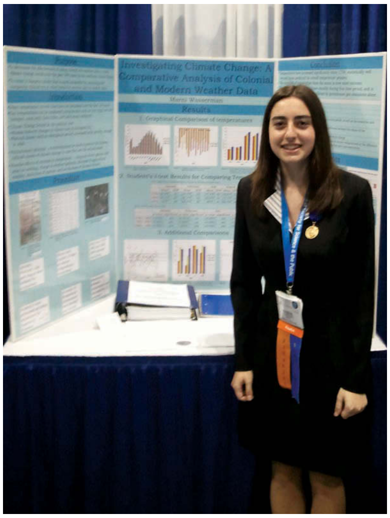
The AMS was among 64 professional, industrial, educational, and governmental organizations providing judges to administer special awards at the ISEF. The AMS judging team included Leslie Belsma, John Bohlson, and Anthony Stier of the Aerospace Corporation in El Segundo, California. Charles Holliday of the Air Force Weather Agency, Offutt Air Force Base, Nebraska, served as judge chairman.

The ISEF includes 17 disciplinary categories ranging from animal sciences to environmental management. Often, AMS award winners come from the core Earth sciences category. However, AMS judges may find atmospheric-related projects in other categories, such as mathematics, computer science, physics and astronomy, engineering, and environmental sciences, as well as energy and transportation. This year's top winner, Christopher Gerlach, was a competitor in the Earth sciences category.

Exhibits dominating the AMS competition this year featured research in climate change, regional climatology, hurricane modeling, aerosol particle analysis, dispersion modeling, thunderstorm wind events, stratosphere–ionosphere coupling, and volcanic lightning. Projects also encompassed other subjects such as wind energy and solar variability. Of the total individual projects at the ISEF, those related to atmospheric sciences represented about 1% of the exhibits.

First Place: Christopher Aaron Manning Gerlach, T. C. Williams High School, Alexandria, Virginia, "Washington, D.C. Severe Thunderstorm Wind Events: An Analysis of Correlated Thermodynamic Convective Parameters and Doppler Radar Signatures."

The level of sophistication in candidate projects at ISEF is quite high. The majority of the students receive guidance from professional scientists as well as use of selected datasets and facilities at federal institutions and universities. The AMS judging team must sort out how much the student participated in the design of the experiment and in the data analysis. The final, critical step in the judging process is the multiple student interviews, which give the individual judges the opportunity to determine the degree of each student's knowledge, technical skill, and creative ability.



Second Place: Marni Jordyn Wasserman, 18, Commack High School, Commack, New York, "Investigating Climate Change: A Comparative Analysis of Colonial and Modern Weather Data."

The Society awards monetary recognition to the top three winners. All winners receive certificates of achievement. In addition, the Society provides each student a one-year membership and subscription to either the *Bulletin* or *Weatherwise* magazine. Each student also receives an AMS Journal/*Bulletin* archive DVD for the previous year. For widespread recognition, all ISEF participants with projects related to AMS interests receive lapel pins and information brochures.

First-Place Award: Christopher Aaron Manning Gerlach, 16, a sophomore at T. C. Williams High School, Alexandria, Virginia, received the AMS special award of $2,000 for the best atmospheric exhibit at the ISEF. His project was titled "Washington, D.C. Severe Thunderstorm Wind Events: An Analysis of Correlated Thermodynamic Convective Parameters and Doppler Radar Signatures."

Second-Place Award: Marni Jordyn Wasserman, 18, a senior at Commack High School, Commack, New York, garnered the AMS second-place award of $1,000 for her project, "Investigating Climate Change: A Comparative Analysis of Colonial and Modern Weather Data."

Third-Place Award: Kyra Hollister Grantz, 17, a senior at the York School, Monterey, California, secured the AMS third-place award of $500. Her project was titled "The Effect of Ocean Temperature on Aerosol Particle Absorption."

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Honorable Mention Winners: Jessica Marie Constant, 15, a sophomore at Poudre High

School, Fort Collins, Colorado, for her project "Computer Modeling IV: A Particulate Dispersion Model Employing Real-Time Wind Calculations"; the team of Nobutada Kawazoe, Taiki Maehata, and Rushia Kanai, all 17 and juniors at the Kagoshima Prefectural Kinkowan Senior High School, Kagoshima, Japan, for their project "Characterization of Volcanic Lightning and Modeling How Volcanic Lightning Occurs at Sakurajima Volcano in Kagoshima, Japan"; and Cayley Erin Dymond, 15, a junior at North Point High School for Science, Technology, and Industry, Waldorf, Maryland, for her project "Stratosphere–Ionosphere Coupling: The Effects of Sudden Stratospheric Warming on the Ionosphere."

—Charles R. Holliday

2011 Science Fairs

The AMS awards Certificates of Outstanding Achievement to student exhibitors for creative scientific endeavor in the areas of atmospheric and related oceanic and hydrologic sciences at regional and state fairs affiliated with the Intel International Science and Engineering Fair. Listed below are AMS award winners from the 2011 fairs.

ALABAMA

ALABAMA SCIENCE AND ENGINEERING FAIR

John Christopher Ashburn, Covenant Christian Academy, "Asteroid Impact Tsunamis: A Continuation"

Erica Lyn Blackstock, Brooks High School, "Light Pollution: How Clear is Clear?"

Anna Elizabeth Pope, Patrician Academy, "Gulf Oil Spill"

ARIZONA

YOUTH ENGINEERING AND SCIENCE FAIR

Natalie Dyjak, homeschooled, "Erosion: Going, Going, Gone . . . (Year 2)"

ARKANSAS

ARKANSAS SCIENCE AND ENGINEERING FAIR

Jeremy Light, Star City High School, "Is Rain Harmful?"

CALIFORNIA

2011 SYNOPSYS CHAMPIONSHIP

Chung Jui Yu, Lynbrook High School, "Mapping the Time-Averaged Distribution of Combustion-Derived Air Pollutants in the San Francisco Bay Area"

Zahra Masood, Granada Islamic School, "Carbon Dioxide and Global Warming"

SACRAMENTO REGIONAL SCIENCE AND ENGINEERING FAIR

William Fong and Guillemma Subia-Smith, California Middle School, "Hydrometers and Psychometers"

TRI-VALLEY SCIENCE AND ENGINEERING FAIR

Ciaron Bench, Livermore Charter School, "The Effect of Earth's Magnetic Field on Cosmic Rays"

USCA12 MONTEREY COUNTY SCIENCE AND ENGINEERING FAIR

Kyra Grantz, York School, "Effects of Ocean Temperature on Aerosol Particle Absorption"

COLORADO

DENVER METROPOLITAN SCIENCE AND ENGINEERING FAIR

Mimi Kim, American Academy, "A Comparison of the pH Levels of a Variety of Samples of Rainwater from Different Parts of the World"

CONNECTICUT

CONNECTICUT SCIENCE FAIR

Nicole M. Terrizzi and Margaret M. Gallagher, St. Mark School, "Desalination!"

Erika M. Diaz and Goddess Gilbert, SS. Cyril and Methodius School, "Wind Turbines! How Much Electric Energy can be Produced by Wind Turbines?"

DELAWARE

DELAWARE VALLEY SCIENCE FAIR

Reginald Johnson, Wise and Pure Home School, "Examining the Accuracies of the Global Forecast System and the North American Mesoscale Model"

Aubrey Paris, Delran High School, "Cloudy with a Chance of Acid: Exploring the Creation and Effects of Acid Rain"

Alisha Khan, Methacton High School, "Katrina, Andrew, and Ike! Predicting the Next Major Hurricane Season"

Andrea Jin, Upper Dublin High School, "Accuracy of Weather Forecasts"

Robert Jaquette, Charter School of Wilmington, "Oil vs. Hurricanes"

Lexus Brown, Woodstown High School, "What Color Glass Traps the Most Heat?"

Sarah Codd, Downingtown Middle School, "Tsunami Waves"

Joshua Awokuse, Towle Institute, "Predicting the Weather"

FLORIDA

ALACHUA REGION SCIENCE AND ENGINEERING FAIR

Michael Morse, Kanapaha Middle School, "HOT, HOT, HOT Solar Water Shower"

BIG SPRINGS REGIONAL SCIENCE FAIR

Caare Jacobsen, Belleview High School, "Acid Rain: The Plants, The Waters"

Alex Stubblebine, Cornerstone School, "The Fish Need to Breathe!"

Jessica Rockey, The Villages Charter Middle School, "Which Material Absorbs Oil the Best in Fresh and Salt Water?"

Perla Rico, The Villages Charter High School, "How is Global Warming Affected by Carbon Dixon?"

BREVARD SOUTH INTRACOASTAL MAINLAND SCIENCE AND ENGINEERING FAIR

Amber Flanagan, Space Coast Jr./Sr. High School, "Hurricanes vs. Typhoons"

CITRUS REGIONAL SCIENCE AND ENGINEERING FAIR

Alicia Keiser, Academy of Environmental Science, "Which River Has More Chemicals?"

Kaleb Jemison, Academy of Environmental Science, "Barnacle Intrusion of the Crystal River System"

HILLSBOROUGH REGIONAL SCIENCE FAIR

Cesar E. Jaeda Jr., Wharton High School, "Efficiency of Vertical Wind Turbines Using Coastal Wave Energy Converters"

LAKE REGIONAL SCIENCE AND ENGINEERING FAIR

Lily Edelstein, Tavares Middle School, "Sinkholes"

LOCKHEED MARTIN MANATEE REGIONAL SCIENCE & ENGINEERING FAIR

Alexander Soto, Braden River Middle School, "Botanical Rooftops: Energy Savers?"

Shawna McInnis, Palmetto High School, "What Barrier to Wind Erosion is Most Effective?"

SOUTH FLORIDA SCIENCE ENGINEERING FAIR

Abigail Ayers, North Miami Beach Senior High School, "Hurricane Spoilers, Part 2"

Daniel Chomat, Christopher Columbus High School, "The Effect of Hurricane Force Winds on High Profile and Medium Profile Tiles"

STATE SCIENCE AND ENGINEERING FAIR OF FLORIDA

Joseph G. Hernandez, Spruce Creek High School, "Effect of Stratospheric Cooling on Tropical Cyclones"

Margaret K. Parrish, Adams Middle School, "The Relationship between the pH Levels and the Source Regions of West Central Florida Rainfall"

GEORGIA

COASTAL GEORGIA REGIONAL SCIENCE AND ENGINEERING FAIR

Joe Kelley, Brunswick High School, "Metal Meltdown"

Peri Odachowski, St. Simons Christian School, "Evaporation Sensation"

CSRA SCIENCE AND ENGINEERING FAIR

Kaitie Counts, Batesburg-Leesville High School, "Which Section of Town Has More Air Pollution?"

GEORGIA SCIENCE AND ENGINEERING FAIR

Ja'Sharee Bush, North Clayton High School, "Water Quality: Upstream Versus Downstream Phase II"

Eric Lau, Savannah Arts Academy, "Sustainable H_2 Production: Acoustic Cavitation at a SOEC Cathode"

GEORGIA TECH SAVANNAH REGIONAL SCIENCE AND ENGINEERING FAIR

Christopher Michael Caster, H. V. Jenkins High School, "Can Energy be Obtained from the Tidal Creek?"

Michael Polak, Coastal Middle School, "Wave Energy on Tybee Island"

ROCKDALE REGIONAL SCIENCE AND ENGINEERING FAIR

Anthonia Adams, Rockdale Magnet School for Science and Technology, "The Effect of Soil Permeability on the Release of Gases Resulting in Acid Rain after a Mudslide"

Lori Brown, Rockdale Magnet School for Science and Technology, "Potentially Hazardous Emissions of Chemicals from Cardboard"

HAWAII

HAWAII STATE SCIENCE & ENGINEERING FAIR

Marissa K. Encarnacion and Byron J. Scofield, St. John Vianney School, "Colored Fabric vs. Weather"

INDIANA

NORTHEAST INDIANA REGIONAL SCIENCE & ENGINEERING FAIR

Mary Rumsey, Woodside Middle School, "Whether or Not, Weather?"

NORTHEASTERN INDIANA TRI-STATE REGIONAL SCIENCE FAIR

Olivia Dornbush, Fremont Elementary School, "Under Pressure"

Nick Dye, DeKalb High School, "Meteorites: Does Size Matter?"

NORTHWESTERN INDIANA SCIENCE AND ENGINEERING FAIR

Nicole Malouhos, Boone Grove High School, "Are Your Suds Safe?"

TRI-STATE SCIENCE AND ENGINEERING FAIR

Nikki Dixon, Castle North Middle School, "Hairy Hygrometers"

KENTUCKY

NORTH AREA COUNTIES OF KENTUCKY EXPOSITION OF SCIENCE

Claire Reinert, Notre Dame Academy, "Evaluation of SODIS Disinfection Method"

Derek Cummins, Williamstown Middle School, "Earthquake Crazies"

LOUISIANA

GREATER NEW ORLEANS SCIENCE & ENGINEERING FAIR

Caleb Gestes, John Curtis Christian, "Lightning in a Bottle: Phase 1"

Tim Luwe, John Curtis Christian, "Type of Soil Has an Effect on the Amount of Concentration of Contaminants Potentially Reaching the Water Table"

LOUISIANA SCIENCE AND ENGINEERING

Morgan DeCuir, St. Joseph`s Academy, "Why Have the Number of Neuroinvasive Cases of West Nile Virus Decreased?"

Alexandra Badeaux, Catholic High School, "Bird's Eye View: Development of a Method to Determine Gender in Green Cheek Conures"

MASSACHUSETTS

REGION III SCIENCE AND ENGINEERING FAIR

Margaret R. Perkins, Taunton High School, "Does Age Affect the Accuracy of Eyewitness Testimony?"

Tess D. Cushing, Taunton High School, "Is the Bioluminescence of Pyrocystis Fusiformis Affected by Changes to its Dark/Light Cycle?"

Jessen N. Foster, Bishop Feehan High School, "Transpiration"

MICHIGAN

DETROIT REGIONAL SCIENCE AND ENGINEERING FAIR

Nathan Alan Lee, Oakland Steiner, "The pH and TDS of the Snow in Southeast Michigan"

Natalie Grossman, Our Lady of Good Counsel, "What Color of Light is the Brightest through Fog?

Ahmad Hider, Dearborn Center for Math, Science, and Technology, "Geomagnetic Effects on the Wide Area Augmentation System"

Alayah Martin, Ann Arbor Trail Open Middle School, "The Mathematics of Snowflakes"

Natalie Nagpal, Morenci High School, "The Irreversible Effects of Greenhouse Gases on Tropical and Desert Biomes"

ROCHESTER REGIONAL SCIENCE FAIR

Kate Geschwind, May High School, "Developing Analytical Approaches to Forecast Wind Farm Production: Phase II"

SOUTHEAST MICHIGAN SCIENCE FAIR

Maya Gianchandani, Skyline High School, "How Quickly is the Water Table Dropping in Certain Cities—e.g., in Phoenix, Arizona, and What is the Cause of It?"

MINNESOTA

DAVID F. GRETHER CENTRAL MINNESOTA REGIONAL SCIENCE FAIR

Nathan Juettner and Dylan Sewald, Champlin Park High School, "What is the Effect of Martian Terrain on Plants and Organisms?"

ST. PAUL REGIONAL SCIENCE FAIR

Laura J. Souther, Cyber Village Academy, “Rain Rain Go Away! Come Again a Cleaner Way!”

Keith B. Eicher, Murray Junior High School, “How Does the Acidity of a Plant’s Water Affect Its Height?”

SOUTH CENTRAL/SOUTHWEST MINNESOTA REGIONAL SCIENCE AND ENGINEERING FAIR

Brian Prchal, New Prague High School, “Can Wind Turbine Designs Enhanced by Biomimicry Increase the Efficiency of Wind Energy?”

Mike Hirsch and Nathan Lax, St. Mary’s High School, “The Effects of Altitude on Solar Cells”

Savannah Zippel, Minnesota New Country School, “Can You Take the Heat? A Study of Thermal Expansion and Minerals”

Mark Broderius, Lincoln Junior High School, “Comparing the Efficiencies of Ethyl Alcohol from Various Organic Materials”

Isaac Griebel, New Ulm Area Catholic School, “Do Different Liquids Affect how a Surface Tension-Powered Raft Operates?”

SOUTHEAST MINNESOTA/WESTERN WISCONSIN REGIONAL SCIENCE FAIR

Preston Frie, Cochrane-Fountain City High School, “Micro Environment Wind Capacity”

TWIN CITIES REGIONAL SCIENCE FAIR

Jenna J. Grundtner, Presentation of the Blessed Virgin Mary, “$C0_2$ and Plant Growth”

Ethan A. Davenport, Cyber Village Academy, “North vs. South: pH Water Testing”

WESTERN SUBURBS REGIONAL SCIENCE FAIR

Charlotte C. Cowdery and Claudia Cerda-Escobar, Jefferson Community School, “Water Quality in Minneapolis Lakes”

Miranda N. Smith, Hopkins North Junior High School, “The Neutralization of Acid Rain”

MISSISSIPPI

MISSISSIPPI REGION VI SCIENCE AND ENGINEERING FAIR

Logan Leake, Ocean Springs High School, “The Presence of Nitrates in Local Bodies of Water”

Taylor Trippe, St. Patrick Catholic High School, “Coastal Non-Point Source Pollution”

MISSOURI

GREATER KANSAS CITY SCIENCE AND ENGINEERING FAIR

Cheena Padmanabhar, Olathe North High School, “How Sea Level Rise Causes Agriculture to Impact Global Economies”

Samantha Farb, Ashima Home School, “Does Precipitation Increase or Decrease Tornadoes?”

MID-AMERICA REGIONAL SCIENCE AND ENGINEERING FAIR

Elsa Kunz, Central High School, “Large Scale Wind Farms’ Influence on Weather Patterns”

SOUTHEAST MISSOURI REGIONAL SCIENCE FAIR

Abby Breite, Trinity Lutheran School, “Air Particulates and Location”

MONTANA

BILLINGS CLINIC RESEARCH CENTER SCIENCE EXPO

Steven Drake, Luther School, “Flake Files”

Anna Miller, McKinley School, “Can You Make Fog without a Fog Machine?”

NEVADA

ELKO COUNTY SCIENCE FAIR

Leanna Dann, Owyhee High School, “Germinating Pinyon Seeds for Reforestation and Carbon Sequestration”

Kyndra Smith and Alyssa Stewart, Owyhee High School, “Carbon Dioxide and Heat Retention”

NEW MEXICO

CENTRAL NEW MEXICO SCIENCE AND ENGINEERING RESEARCH CHALLENGE

John Valdez, Rio Rancho High School, “CO_2 Reduction; Employing Natural Absorbents Phase 3”

Jamie Heinlein, Los Lunas High School, “How Rich Is Your Soil? The Effect of Pesticides on Soil Types”

FOUR CORNERS REGIONAL SCIENCE & ENGINEERING FAIR

Tyler Knapton, Grants High School, “Atmospheric CO_2 Scrubbing”

Cayden J. Wilson, Grants High School, “Predicting Drought”

NEW MEXICO SCIENCE AND ENGINEERING FAIR

Travis Crockett, Cleveland High School, "Modeling and Design of a Low Earth Orbit Space Debris Amateur Tracking Station"

Philip Lane, Aztec High School, "Weather or Not: Seasons Change"

NATIONAL AMERICAN INDIAN SCIENCE AND ENGINEERING FAIR

Courtney Jackson, Cloquet High School, "The Coronae Paradox: Use of Visual Basic to Determine Circular Low Formation Based Upon Maps Created Using Magellan Data Used to Determine the Overall Geologic History of Circular Lows on Venus"

Destiny Salmon, Tsuk Taih School, "The Effects of Climate Change on Traditional Athabascan Diet in the Interior of Alaska"

NEW YORK

DR. NELSON YING TRI REGION SCIENCE AND ENGINEERING FAIR

McGinnis Miller, Maine-Endwell Middle School, "How Salty is Pamlico Sound Compared to the Atlantic Ocean and How Much Salt is in the Waters of Hatteras Island, NC?"

NORTH CAROLINA

NORTH CAROLINA SCIENCE ENGINEERING FAIR

Miles Wobbleton and Danielle Romack, D. H. Conley High School, "The Effects of Driving Style on Fuel Conservation, Fossil Fuel Resources, and the Environment"

Matthew Miller, Western Alamance High School, "Root Airfoil Vortex Generators Improve the Aerodynamics of Wind Turbine Blades"

SOUTHEASTERN NORTH CAROLINA REGIONAL SCIENCE FAIR

Amanda Padgett, Leland Middle School, "Eco-Friendly Oil Spill Clean Up"

Robert Stone, Isaac Bear Early College High School, "Different Materials for Sand Bags"

Zane Hill, Cedar Grove Middle School, "Big Deal about Ethanol"

UNIVERSITY OF NORTH CAROLINA-CHARLOTTE REGIONAL FAIR

Geard Fossett, Country Day High School, "Developing a Solar Energy Harvesting System for Wireless Sensors"

NORTH DAKOTA

NORTH DAKOTA SOUTHWEST CENTRAL REGIONAL SCIENCE FAIR

Kate Fox, Wing High School, "Pressured?"

Lucas Nistler, Glen Ullin High School, "Melting Matters"

OHIO

MARION AREA SCIENCE & ENGINEERING FAIR

Joseph Hickman, John C. Dempsey Middle School, "A Comparison of Pond Type and Water Quality"

OKLAHOMA

NORTHWESTERN OKLAHOMA REGIONAL SCIENCE FAIR

Kelton Nance, Vici Public School, "Fuel Today, Heat Tomorrow"

OREGON

CENTRAL WESTERN OREGON SCIENCE EXPO

Lipi Gupta, Crescent Valley HS, "Pulse Responses of Soil CO_2 Efflux to Rain Events in a Ponderosa Pine Forest in Central Oregon"

Loren Deyo-Rivera, Karen LaGesse, and Emily Midyette, Lighthouse School, "Which Soil Types Resist Soil Liquifaction?"

CREST-JANE GOODALL SCIENCE SYMPOSIUM

Jenna Wiegand, Wilsonville High School, "Eco Designs: Reflective Roofing Solutions"

Nick Trese, Wilsonville High School, "Utilizing Fog and Water Vapor as Sources for Potable Water"

INTEL NORTHWEST SCIENCE EXPO

Kiernan Garrett and Alessandra Elliott, Merlo Station High School, "Effects of Simulated Climate Change in an Open Air Environment on Arbuscular Mycorrhizal Fungi in Zea Mays Indentata"

PENNSYLVANIA

NORTH MUSEUM SCIENCE AND ENGINEERING FAIR

Michael Bressi, Garden Spot High School, "Solar Energy vs. Turbine Energy"

Aimee Little, Lancaster Catholic High School, "The Effect of Tidal Influence and Seasonal Change on the Water Quality of an Estuary"

PITTSBURGH REGIONAL SCIENCE AND ENGINEERING FAIR

Darien Page Sr., Thea Bowman Catholic Academy, "How's the Weather Up There?"

Nathan Rogers, Eden Christian Academy, "Measuring Relative Humidity"

Sarah Sokol, Freeport Senior High School, "Fly Ash's Effect on Ryegrass"

SOUTH CAROLINA

LOWCOUNTRY SCIENCE AND ENGINEERING FAIR

Matthew Hunter, Academic Magnet High School, "Slick Science"

Sally Hunt, Academic Magnet High School, "Bioaccumulation of Heavy Metals in Oysters"

PIEDMONT REGION III SCIENCE FAIR

Maranda Martin, John E. Ewing Middle School, "How Does Acid Rain Destroy Statues?"

Indy Singleton, Granard Middle School, "A Change in the Winds-Experimenting with Bernoulli's Principle"

SOUTH DAKOTA

EASTERN SOUTH DAKOTA SCIENCE AND ENGINEERING FAIR

Seth Petra, Elk Point Jefferson, "Shaping Wind Energy"

Taylor R. Branson, Elk Point Jefferson, "Tornado"

NORTHERN SOUTH DAKOTA SCIENCE AND MATHEMATICS FAIR

Cassius Pond, Ipswich School, "Rockets Away III"

Amber Anderson, Waubay School, "Fluorescent versus Incandescent"

TENNESSEE

MIDDLE TENNESSEE SCIENCE AND ENGINEERING FAIR

Daniel Thomas Lawhon, Greenbrier High School, "Effects of the Firing Process for Eastern Dark-Fired Tobacco on Air, Water, and Soil Quality"

SOUTHERN APPALACHIAN SCIENCE AND ENGINEERING FAIR

Eric O'Reilley, West Valley Middle School, "Efficiency of a Solar Cell: Orientation, Angle, and Shading"

Leyton Mullins, The King's Academy, "Sun + Solar Cell + Rechargeable Batteries = Green R/C Fun"

WEST TENNESSEE REGIONAL SCIENCE AND ENGINEERING FAIR

Bayleigh Powers, Union City Middle School, "Frizz or Flat: Can Hair Measure Humidity?"

Nathaniel Hubbs, Camden Central High School, "Investigation of Climate Trends and Terrestrial Salamander Densities"

UTAH

CENTRAL UTAH SCIENCE AND ENGINEERING FAIR

Diana Smith, Rocky Mountain Middle School, "Oily Feathers"

Chandler Holgate, Summit Academy, "Ocean Acidification"

Sienna Wagstaff, Rocky Mountain Middle School, "Midways Geothermal Jackpot"

SALT LAKE VALLEY SCIENCE AND ENGINEERING FAIR

Nikolaos Liodakis, Hillcrest High School, "Novel Simulation of Enhanced Chemical Precipitation Treatment of Heavy Metals in Contaminated Wastewater"

SOUTHERN UTAH SCIENCE AND ENGINEERING FAIR

Logan Carter and Jeremy Batt, SUCCESS Academy, "Wind Energy"

Breann Clark and Soriano Elizabeth, SUCCESS Academy, "Bullhog Treatment"

Tyler Herrera and Robb Etzel, Mont Harmon Jr. High School, "Altitude and Oxygen"

Korrin Olson, Mont Harmon Jr. High School, "What Type of Water Do Goldfish Live Best In?"

VIRGINIA

BLUE RIDGE HIGHLANDS REGIONAL SCIENCE FAIR

Robert Wills, SWVGS/Narrows High School, "Arctic Research Sensor Array"

Ian Ho, Classical Conversations of Christiansburg, "Wind Power"

PIEDMONT REGIONAL SCIENCE

Cassandra Bard, Anna Ware, and Alicia Schmertzler, Western Albermarle High School, "Assessment of Particulates Matter Found in Selected Zip Codes in Albemarle County"

Li Yujian, The Covenant School, "The Relationship between Air Humidity and Electrical Conductivity"

WASHINGTON

MID-COLUMBIA REGIONAL SCIENCE AND ENGINEERING FAIR

Adam Lewis, Christ the King School, "Pollution Solution"

INTERNATIONAL SCIENCE FAIRS

BRAZIL

FEIRA BRASILEIRA DE CIÊNCIAS E ENGENHARIA

Barbara Villas Boas Freire de Almeida, Flavia Caroline Faggiao, and Nayara Martins Orsi, Colegio Inerativa, "Analysis of Planktonic Communities of the Coast of Parana"

Karoline Schallenberger, Fernanda Bohn, and Anelise Pittella de Freitas, Colegio Luterano Arthur Konrath, "Underwater Electric Power Generator System"

Rochelly Reis de Sousa, Ewerton Gomes dos Santos, and Aleff Silva de Lucena, Escola Julia Giffoni, "Monitoring of Marine Benthic Macroalgae Beach Pacheco, Caucaia-Ceara, Using as a Comparative Project of the Ecological and Economic Zoning of the State of Ceara"

CHINA

SHANGHAI ADOLESCENTS SCIENCE & TECHNOLOGY INNOVATION FAIR

Zhihao Yin, Tongji University Experimental School, "Remote Sensing Evaluation of the Fundamental Environment Quality of Shanghai World Expo 2010 Park"

SICHUAN REGIONAL ISEF AFFILIATED FAIR

SeungWon Paik and YangSun Kim, Tianjin International School, "Acid Rain"

ITALY

I GIOVANI E LE SCIENZE 2011

Umberto Lavagnolo, Liceo Scientifico Statale Galileo Galilei, "An Aquarium at Microscope. Study of Zooplanktonic Component in a Spring Environment Reproduced in Laboratory"

ROMANIA

ROMANIAN INTERNATIONAL SCIENCE AND ENGINEERING FAIR

Alina Mitrici and Andrei Rata, Petru Rares National College, "Study of Atmospheric Magnetic Fields"

RUSSIA

ROST FAIR

Ekaterina Shirokova, School #2 of Dzerzhinsk, "Mist Blooming with and Electric Field"

AMS MEMBERS AND CHAPTERS

CALIFORNIA

LOS ANGELES COUNTY SCIENCE FAIR

The Los Angeles chapter of AMS chose two winners for the best weather-related projects at the 61st Annual Los Angles County Science Fair, held at the Pasadena Convention Center 15 April 2011. This year both winners were from the junior (middle school) division. Both were chosen for their creativity and scientific discovery.

The first-place winner, Samantha Stott, Miraleste Intermediate School, Palos Verdes Peninsula Unified School District, presented her project, "Where Does California's Rain Come From?" Samantha collected rain over a three-month period and analyzed the O_{18}/O_{16} ratios to determine whether the rains were from a tropical or polar source. She found that there were distinct differences in the ratio between the source areas. Samantha also checked water vapor satellite imagery to verify the trajectory of moisture plumes. This December, Los Angeles had copious amounts of rain from an atmospheric river of tropical moisture, which showed up well in Samantha's data.

The second-place winner, Elizabeth Bissell, Robert A. Millikan Middle School, Los Angeles Unified School District, collected snow samples from several cities in North America and Europe, in her project titled, "Snow Globe." Snow samples were analyzed for pH, lead, and nitrates and then compared with city population size. Her hypothesis was that larger cities would have more pollutants than smaller cities. Overall, the results confirmed her hypothesis.

Both winners of the 2008 LA County Science Fair received subscriptions to *Weatherwise* and invitations to the LA chapter banquet.

GEORGIA

NORTHEAST GEORGIA REGIONAL SCIENCE AND ENGINEERING FAIR

AMS Member Thomas Mote judged the this year's fair. The winning project was a team of Abby Rogers and Bridgett Caroll of Commerce Middle School for their project "Hurricane Proof."

ILLINOIS

IJAS REGION 5 SCIENCE AND ENGINEERING FAIR

AMS Member Stephen Strader and member of a local AMS chapter did the judging for the science fair in DeKalb. The winners were:

Caroline Hutton, Dundee-Crown High School, "Rooftop Gardens"
Aleta Soron, The Einstein Academy, "Effects of Flooding"

TEXAS

ALAMO REGIONAL SCIENCE AND ENGINEERING FAIR

AMS Member Robert Blaha judged the fair in San Antonio. The winners were:

Aidan Watson-Morris, Communications Arts High School, "The Correlation between Submarine Offshore Shelf Dimensions and Tsunami Height"
Shari Rohert, Keystone School, "Stimulating Growth in Phaseolus Lunatus Using Low Amperage Current on the Fibrous Root Systems"
Jaclyn Guz, Churchill High School, "Did They Recover from Drought? A Comparison of Juniperous Ashei and Quercus Virginiana in a South Texas Native Park"
Mary Lavender and Ariel Jones, Madison High School, "Can't Touch This—A Study of the Effect of Various Paving Materials on Urban Island Heating"
Ruiqi He, Katherine Stinson Middle School, "Is the Increasing Amount of Carbon Dioxide Really Causing Glacier Melting Rates to Increase?"
Leland Ott, Mountain Valley Middle School, "Leaf Decomposition—The Art of Becoming Dirt"
Alejandro Martinez, Harris Middle School, "Die Tornadoes"
Connor Lathrop, Spring Branch Middle School, "Weather on Solar Output"
Parker Ray and Timothy Wright, Leakey ISD, "Affects of Acid Rain on Plants"

AUSTIN ENERGY REGIONAL SCIENCE FAIR

AMS Members Troy Kimmel, Bob Rose, and Robert Blaha judged the Junior and Senior Division Science Projects at the Austin Energy Science Festival 2011.

The Austin Energy Regional Science Festival is one of Texas's largest regional science fairs, with more than 3,500 students from the 1st through the 12th grade. It encourages and rewards innovative student research and provides scientists, engineers and other professionals a chance to volunteer in the community. The winners were:

Aaron Hui and Kim Ed, Westwood High School, "Modeling Dust Devils"
Shankar Srinivassan, Bryan High School, "How Renewable is College Station's Ground Water?"
Katie Lecornu, Bowie High School, "Weekly Air"
Parker Hopkins, Walsh Middle School, "Tornadoes"
Serena Zadoo, Anderson High School, "Analyzing the Detrimental Effects of Acid Rain"
Hassan Takir, Harmony SA North High School, "Prime Coat"
Nadege Lebert, Harmony SA North High School, "Predicting the Weather"
Yasmeen Tizani, Austin Peace Academy, "Impact of Global Warming on Plant Growth"
Sydnie Chatman, Grisham Middle School, "Global Warming and CO_2"
Ryan McBroom, Walsh Middle School, "Turning the Red Planet Green"

CANADA

NIAGARA REGIONAL SCIENCE AND ENGINEERING FAIR

Andrew Ross, AMS Member and the president of the Western New York Chapter, was a judge at the fair in Ontario. The winner of the AMS Certificate of Achievement was Aleksander Gibson, Wehater School, for his project, "Homemade Weather Station."

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

JANUARY

11th Annual AMS Student Conference and Career Fair, 21–22 January, New Orleans, Louisiana
Abstract deadline: 3 October 2011
Registration deadline: 11 January 2012
Initial announcement published: June 2011

AMS Short Course on Space Weather: Space Weather: What is it and who needs to know about it? 22 January, New Orleans, Louisiana
Preregistration deadline: 1 December 2011
Initial announcement published: Aug. 2011

AMS Short Course on The Art & Science of Forensic Meteorology, 22 January, New Orleans, Louisiana
Preregistration deadline: 1 December 2011
Initial announcement published: Sept. 2011

AMS Short Course on Using Python in Climate and Meteorology: Advanced Methods, 21–22 January, New Orleans, Louisiana
Preregistration deadline: 1 December 2011
Initial announcement published: Sept. 2011

AMS Short Course: A Beginner's Course to Using Python in Climate and Meteorology, 21–22 January, New Orleans, Louisiana
Preregistration deadline: 1 December 2011
Initial announcement published: Sept. 2011

NOAA-Sponsored Workshop: Primer on Data Management, 22 January, New Orleans, Louisiana
Preregistration deadline: 1 December 2011
Initial announcement published: Oct. 2011

***Aksel Wiin-Nielsen Symposium, 23 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: June 2011

***T.N. Krishnamurti Symposium, 26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: June 2011

***28th Conference on Interactive Information Processing Systems (IIPS), 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***26th Conference on Hydrology, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***24th Conference on Climate Variability and Change, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: March 2011

***21st Symposium on Education, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***21st Conference on Probability and Statistics in the Atmospheric Sciences, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: June 2011

***18th Conference on Satellite Meteorology, Oceanography and Climatology/First Joint AMS–Asia Satellite Meteorology Conference, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***17th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: May 2011

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*An exhibit program will be held at this meeting.

***16th Conference on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS), 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***16th Symposium on Meteorological Observation and Instrumentation, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***15th Conference of Atmospheric Science Librarians International (ASLI): Communicating Weather and Climate: Making the Most of the Information, 25–26 January, New Orleans, Louisiana**
Abstract deadline: 3 October 2011
Preregistration deadline: 1 December 2011
Initial announcement published: June 2011

***14th Conference on Atmospheric Chemistry, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***10th Conference on Artificial Intelligence and its Applications to the Environmental Sciences, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***10th Symposium on the Coastal Environment, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: June 2011

***Ninth Conference on Space Weather, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***Eighth Annual Symposium on Future Operational Environmental Satellite Systems, 24–25 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***Seventh Symposium on Policy and Socio-Economic Research, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***Fifth Annual CCM Forum: Certified Consulting Meteorologists, 25 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: TBD

***Fourth Symposium on Aerosol–Cloud–Climate Interactions, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***Third Aviation, Range and Aerospace Meteorology Special Symposium on Weather–Air Traffic Management Integration, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***Third Conference on Weather, Climate, and the New Energy Economy, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: March 2011

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* An exhibit program will be held at this meeting.

AMS CAREER FAIR

22–26 January 2012
New Orleans, Louisana

Need to fill a vacant job position? Looking for information on job openings or graduate school opportunities? Then join us at the Career Fair at the 92nd AMS Annual Meeting in New Orleans, Louisiana!

Highlights of the fair:

- Easy access throughout the week to job announcements and resumes
- A message center to communicate with recruiters or prospective students or employees
- An opportunity for on-site interviews

Interested? Additional details are available on our Web site at www.ametsoc.org/MEET/annual or by contacting us at careerfair@ametsoc.org.

***Third Symposium on Environment and Health, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***Second Conference on Transition of Research to Operations: Successes, Plans, and Challenges, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Feb. 2011

***Second Symposium on Advances in Modeling and Analysis Using Python, 22–26 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: May 2011

***IMPACTS 2011: Major Weather Events and Impacts of 2011, 24 January, New Orleans, Louisiana**
Preregistration deadline: 1 December 2011
Initial announcement published: Feb. 2011

***Special Symposium on Technological Advances: Impacts on Hurricane Research and Forecast Improvements, 25 January, New Orleans, Louisiana**
Preregistration deadline: 1 December 2011
Initial announcement published: May 2011

***Special Symposium on the Tornado Disasters of 2011, 25 January, New Orleans, Louisiana**
Abstract deadline: 1 August 2011
Preregistration deadline: 1 December 2011
Manuscript deadline: 22 February 2012
Initial announcement published: Sept. 2011

APRIL

30th Conference on Hurricanes and Tropical Meteorology, 15–20 April, Ponte Verda Beach, Florida
Abstract deadline: 1 November 2011
Preregistration deadline: 12 March 2002
Manuscript deadline: 21 May 2012
Initial announcement published: Aug. 2011

International Conference on Southern Hemisphere Meteorology and Oceanography, 23–27 April, Nouméa, New Caledonia
Abstract deadline: 15 September 2011
Preregistration deadline: 1 February 2012
Initial announcement published: Jan. 2011

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

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

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* An exhibit program will be held at this meeting.

Sponsorship Opportunities Available at AMS Meetings!

The American Meteorological Society's sponsorship program allows your company to stand out in the crowd. Reasonably priced sponsorship packages are available to small through large companies providing the sponsor with quality, value-packed exposure to our meeting attendees. For information contact Claudia Gorski, Director of Meetings, at 617-226-3967; cgorski@ametsoc.org.

MEETINGS OF INTEREST

2011

DECEMBER

19th International Congress of Biometeorology, 5–9 December (ICB 2011), University of Auckland, New Zealand

2012

FEBRUARY

Second National Flood Workshop, 27 February–1 March, Houston, Texas

MARCH

12th National Severe Weather Workshop, 1–2 March, central Oklahoma (location TBA in November)

10th Annual Climate Prediction Applications Science Workshop (CPASW), 13–15 March, Miami, Florida

Eighth International Conference on Air Quality—Science and Application, 19–23 March, Athens, Greece

16th Annual Severe Storms and Doppler Radar Conference, 29–31 March, Ankeny, Iowa

MAY

32nd NATO/SPS International Technical Meeting on Air Pollution Modelling and its Application, 7–11 May, Utrecht, the Netherlands

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, Leipzig, Germany

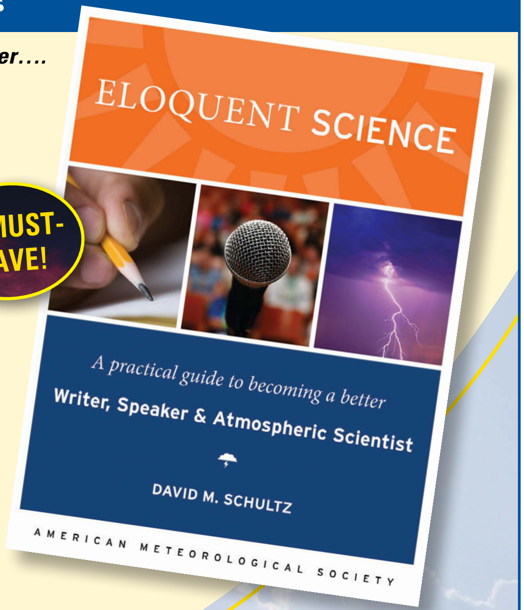
AUGUST

Eight International Conference on Urban Climate (ICUC8) and AMS 10th Symposium on the Urban Environment, 6–10 August, Dublin, Ireland

SEPTEMBER

2012 EUMETSAT Meteorological Satellite Conference, 3–7 September, Sopot, Poland

Third International Conference on Earth System Modelling, 17–21 September, Hamburg, Germany



CALL FOR PAPERS

ANNOUNCEMENT

16th International Symposium for the Advancement of Boundary Layer Remote Sensing, 5–8 June 2012, Boulder, Colorado

The 16th International Symposium for the Advancement of Boundary Layer Remote Sensing will be held 5–8 June 2012 at the University of Colorado in Boulder, Colorado. This year's symposium will be hosted by the Cooperative Institute for Research in the Environmental Sciences at the University of Colorado and the NOAA Earth System Research Laboratory. It will be convened in plenary, oral sessions and poster sessions.

The initial abstract submission process will begin in the late fall of 2011. The registration process will begin in the spring of 2012. If you need an early letter of invitation for a visa application (should include proposed title of paper and authors), please contact isars2012@noaa.gov.

For more information, please contact the conference webpage at www.esrl.noaa.gov/psd/events/2012/isars/. (12/11)

CALL FOR PAPERS

Fifth Chaotic Modeling and Simulation International Conference (CHAOS 2012), 12–15 June 2012, Athens, Greece

The forthcoming Fifth International Conference (CHAOS2012) on Chaotic Modeling, Simulation and Applications (www.cmsim.org) was decided by the previous committee meeting in June 2011 following the successful organization of the 4th CHAOS2011 International Conference.

The study of nonlinear systems and dynamics has emerged as a major area of interdisciplinary research and found very interesting applications. This conference is intended to provide a widely selected forum among scientists and engineers to exchange ideas, methods, and techniques in the field of nonlinear dynamics, chaos, fractals and their applications in general science and in engineering sciences.

The principal aim of CHAOS2012 International Conference is to expand the development of the theories of the applied nonlinear field, the methods, empirical data, and computer techniques as well as the best theoretical achievements of chaotic theory. CHAOS2012 Conference provides a forum for bringing the various groups working in the area of nonlinear systems and dynamics, chaotic theory, and application to exchange views and report research findings.

The deadline for abstracts is *15 December 2011*. For more details please visit the conference website: www.cmsim.org/abstractpapersubmission.html.

For additional information, please contact Anthi Katsirikou, conference secretary (e-mail: secretariat@cmsim.org) or reference the conference website: www.cmsim.org. (12/11)

CALL FOR PAPERS

Croatian–USA Workshop on Mesometeorology, 18–20 June 2012, Zagreb, Croatia

The Croatian–USA Workshop on Mesometeorology will be held 18–20 June 2012 at the Ekopark Kraš Resort near Zagreb, Croatia. The meeting is organized by the Meteorological and Hydrological Service of Croatia, School of Meteorology of the University of Oklahoma, and Geophysical Institute of the University of Zagreb. The Ekopark Kraš Resort is located in the beautiful Kupa River basin within the municipality of Pisarovina. Resort guests are accommodated in wooden cottages and bungalows typical of this region of Croatia.

The workshop will focus on selected problems of today's mesoscale meteorology and will include keynote lectures by scientific experts in the area, presentations by participants, and discussion sessions.

Topics of the workshop include: theory of slope flows and low-level jets; mountain waves and bora-like flows; numerical simulation of turbulent slope flows; modeling of mesoscale flows in mountainous regions; turbulence and land-surface parameterizations for mesoscale models; observational studies of mesoscale flows in complex topography; mesoscale atmospheric convection; data assimilation in mesoscale modeling and numerical weather prediction; and sub-synoptic-scale meteorology and remote sensing.

The total number of the workshop participants is expected to be about 40. The majority of participants will represent Croatia and the United States in approximately equal proportions (~15 from each country) and the rest of participants will be invited contributors from other countries. Limited funds are available to partially cover travel and accommodation costs of Croatian and U. S. participants.

Participants of the workshop are expected to be at graduate-student (advanced M.S. or Ph.D.), postdoctoral, or early career scientist/practitioner levels. The students will be able to file this workshop as a course worth 1 to 3 European Credit Transfer System (ECTS) points depending on a presentation.

To apply for participation submit by *15 January 2012* a brief CV, statement of scientific/operational interests (up to one page), recommendation note from advisor (half page; only for graduate students and post-docs), abstract of the proposed presentation (up to one page with indication of oral/poster preference), and request for financial support with itemization of costs. The cost of full-board accommodation at the Ekopark Kraš Resort is ~€ 50 per day. Submission of applications through e-mail is encouraged.

Croatian participants should submit their applications to Kreso Pandzic, Meteorological and Hydrological Service of Croatia, Grič 3, 10000 Zagreb (e-mail: pandzic@cirus.dhz.hr).

Participants from the United States and other countries should submit applications to Evgeni Fedorovich, School of Meteorology, University of Oklahoma, 120 David L. Boren Blvd., Norman, OK 73072 (e-mail: fedorovich@ou.edu). (12/11)

CALL FOR PAPERS

16th International Conference on Clouds and Precipitation, 28 July–3 August 2012, Leipzig, Germany

The conference is organized every 4 years by the International Commission on Clouds and Precipitation (www.iccp-iamas.org), which is part of the International Association of Meteorology and Atmospheric Sciences (IAMAS, www.iamas.org). The goal of the conference is to provide a venue for the presentation of scientific research in the area of clouds and precipitation and to encourage the exchange of ideas within the international community. The deadline for abstract submissions is *15 December 2011*.

For additional information, please reference the conference webpage at http://iccp2012.tropos.de/index.html. (12/11)

CALL FOR PAPERS

40th Broadcast Meteorology Conference, 22–25 August 2012, Boston, Massachusetts

The 40th Broadcast Meteorology Conference, sponsored by the American Meteorological Society, and organized by the AMS Board of Broadcast Meteorology, will be held in Boston, Massachusetts, 22–25 August 2012. Preliminary programs, registration, hotel, and general information will be posted on the AMS website by late November 2011

Similar to last year's successful conference in Oklahoma City, which was themed upon severe weather, this conference will focus on taking advantage of the wide range of meteorological expertise found in the vicinity of the conference. The location also serves to commemorate the 40th anniversary in close proximity of the AMS headquarters. We plan on interacting with many of the local agencies and research centers, in addition to offering social events and family activities for time outside of the conference sessions in an effort to make the 40th conference something special and not to miss!

Anyone within the general realm of science and technology is invited to submit an abstract. Broadcast meteorologists are especially encouraged as are meteorologists within the general New England/Northeast area in an effort to give some local flavor to the program.

Think back on the past year and the major weather events in your market. Were you affected by one of the historic events of 2011 such as the tornado outbreaks, major drought, rare earthquake, or a landfalling tropical system? If so, we want to hear from you. Did the warning process work and if you could go back, what would you do or how would you handle it differently? What did you do within your weathercast that was revolutionary? What work would you like to share with your peers? How are you using other media platforms to better convey your forecast? Beyond effective communication to the viewer, other welcome topics include the general forecast process, weather analysis and data collection, education, outreach, and duties that extend beyond the forecast and beyond the weather center. Station scientist content is strongly suggested. In an effort to reflect the geography and surroundings of the conference, we also recommend submission of winter weather and coastal weather topics especially this year.

Those in the atmospheric science community beyond television, including the research and operational fields, should consider presenting topics that impact broadcast meteorology. This is a unique opportunity to present to professional communicators that also share in the expertise of atmospheric science. These topics include but are not limited to climate change, operational forecasting, computer technology and graphic development, recent interdisciplinary research projects, atmospheric modeling, and the implementation of dual polarization and phased array radar.

The deadline to submit abstracts is *23 March 2012*. Authors of accepted presentations will be notified by e-mail around 23 April 2012. All abstracts, extended abstracts, and presentations will be available on the AMS website at no cost to viewers.

In addition to the broadcast conference, a one day short course will be held on 25 August 2012. Details will be posted on the AMS website as soon as they become available.

Please do not hesitate to contact any of the conference co-chairs, Rob Eicher (e-mail: rob.eicher@foxtv.com; tel: 407-741-5056), Ross Janssen (e-mail: rjanssen@kwch.com; tel: 316-706-0341), or Maureen McCann (e-mail: maureen.mccann@gmail.com; tel: 781-710-2426) with any questions, comments, or for additional program information. (12/11)

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.

2012 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 2012** 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

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.)

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* 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…

2012 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 2012. A list of Fellows and the process for submitting nominations are on the AMS website (www.ametsoc.org/awards).

2012 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 93rd Annual Meeting (January 2013) 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 2012 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 Corporation
Lockheed Martin Corporation
Northrop Grumman Corporation
Raytheon Company
The Boeing Company
University Corporation for Atmospheric Research
Vaisala, Inc.

REGULAR MEMBERS

1 Source Consulting, Inc.
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 Service
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.
Earth Networks
EKO Instruments Company, Ltd.
Enterprise Electronics Corporation
Environmental Systems Research, Inc.
EWR Weather Radar Systems
Florida State University, Department of EOAS
Global Hydrology and Climate Center
Global Science & Technology, Inc.
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.
MeteoSwiss
Midland Radio Corporation
MSI Guaranteed Weather, LLC
Murray & Trettel, Inc.
National Centre for Medium Range Weather Forecasting
Naval Meteorology and Oceanography Command
NOAA Coastal Services Center
Noblis, Inc.
Optical Scientific, Inc.
Orbital Sciences Corporation
Pelmorex Media Inc.
ProSensing, Inc.
R. M. Young Company
Radiometrics Corporation
Riverside Technology, inc.
Royal Netherlands Meteorological Institute
Science Applications International Corporation
Scintec AG
SeaSpace Corporation
SGT, Inc.
Sonalysts, Inc.
SpectraSensors, Inc.
Sutron Corporation
Telvent DTN
The Weather Channel
U.S Department of Energy, Office of Science
Unisys Corporation
University of Alabama in Huntsville,Earth System Science Ctr
University of Illinois, Department of Atmospheric Sciences
University of Wisconsin - Madison, SSEC
Vieux, Inc.
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The MIT Department of Earth, Atmospheric and Planetary Sciences announces a major expansion of its activities in climate science and seeks applicants for up to three faculty positions in climate-related fields. Preference will be given to junior appointments at the assistant professor level, but a senior appointment can be considered for an individual with exceptional qualifications. Areas of specific interest include observations, models and theory of the atmosphere, ocean and cryosphere, and climates, biogeochemical cycles, and ecology.

The successful candidates will have to have a strong record of accomplishment in their discipline, a strong commitment to teaching and student advising, a keen interest in relating their work to complementary research in the Department and in the MIT/Woods Hole Joint Program in Oceanography. Joint appointments with other MIT departments are also potentially negotiable where appropriate. More information about this position can be obtained by writing Professor Kerry A. Emanuel at emanuel@MIT.EDU.

A completed application will include a curriculum vitae, a statement of research and teaching objectives, and the names of five potential references. Applications are being accepted at Academic Jobs Online - https://academicjobsonline.org/ajo. Please do not ask your referees to upload letters at the time of application; letters will be requested directly by MIT. To receive consideration, a completed application must be received.

Search Contact: Mr. Michael Richard, HR Administrator, EAPS, Massachusetts Institute of Technology, 54-926, 77 Massachusetts Avenue, Cambridge, MA 02139-7307; mjr@mit.edu; 617-253-5184; 617-253-8298 (fax).

MIT is an Equal Opportunity/Affirmative Action employer.
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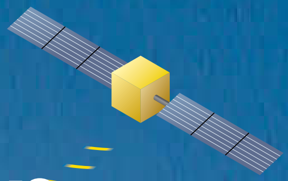

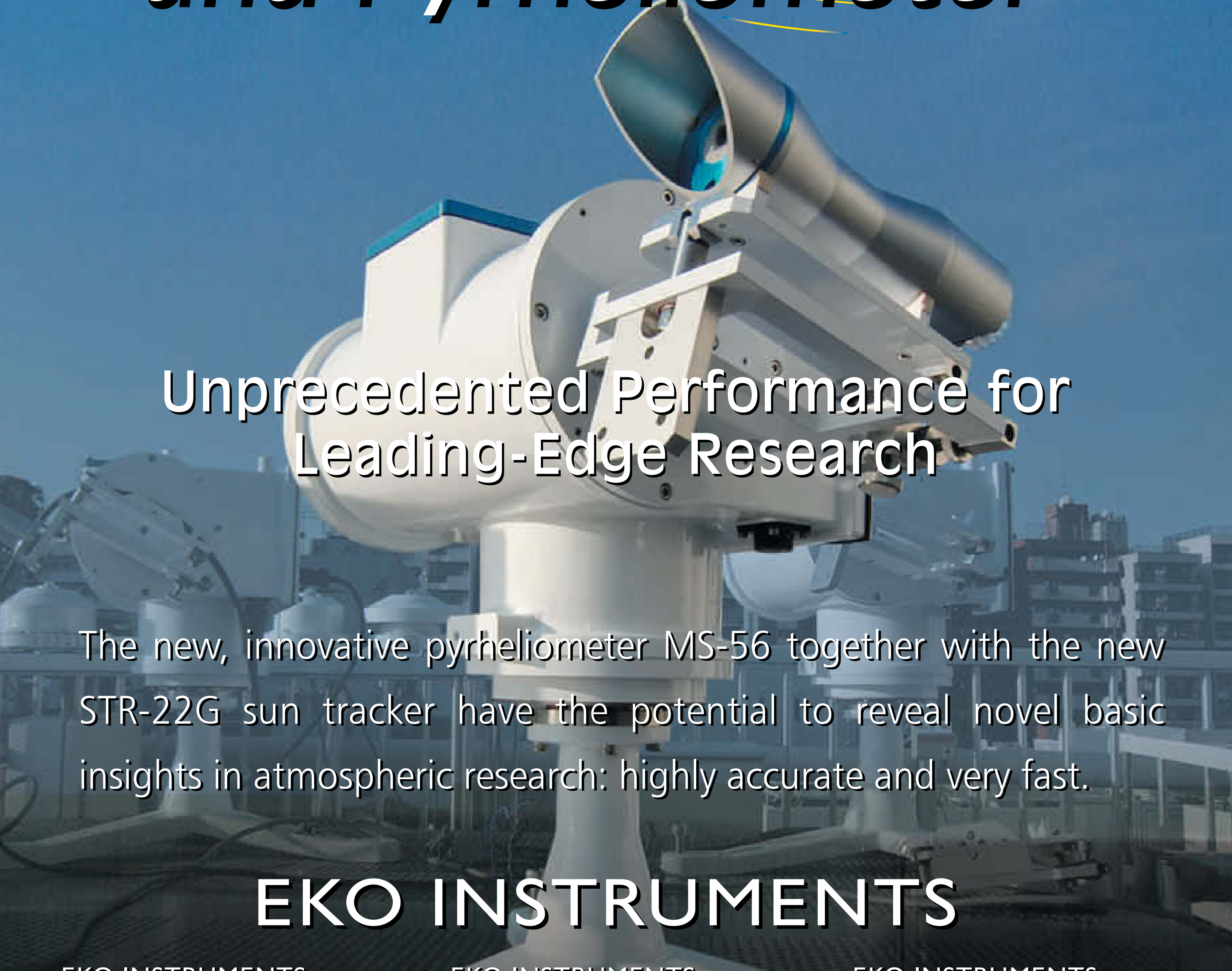

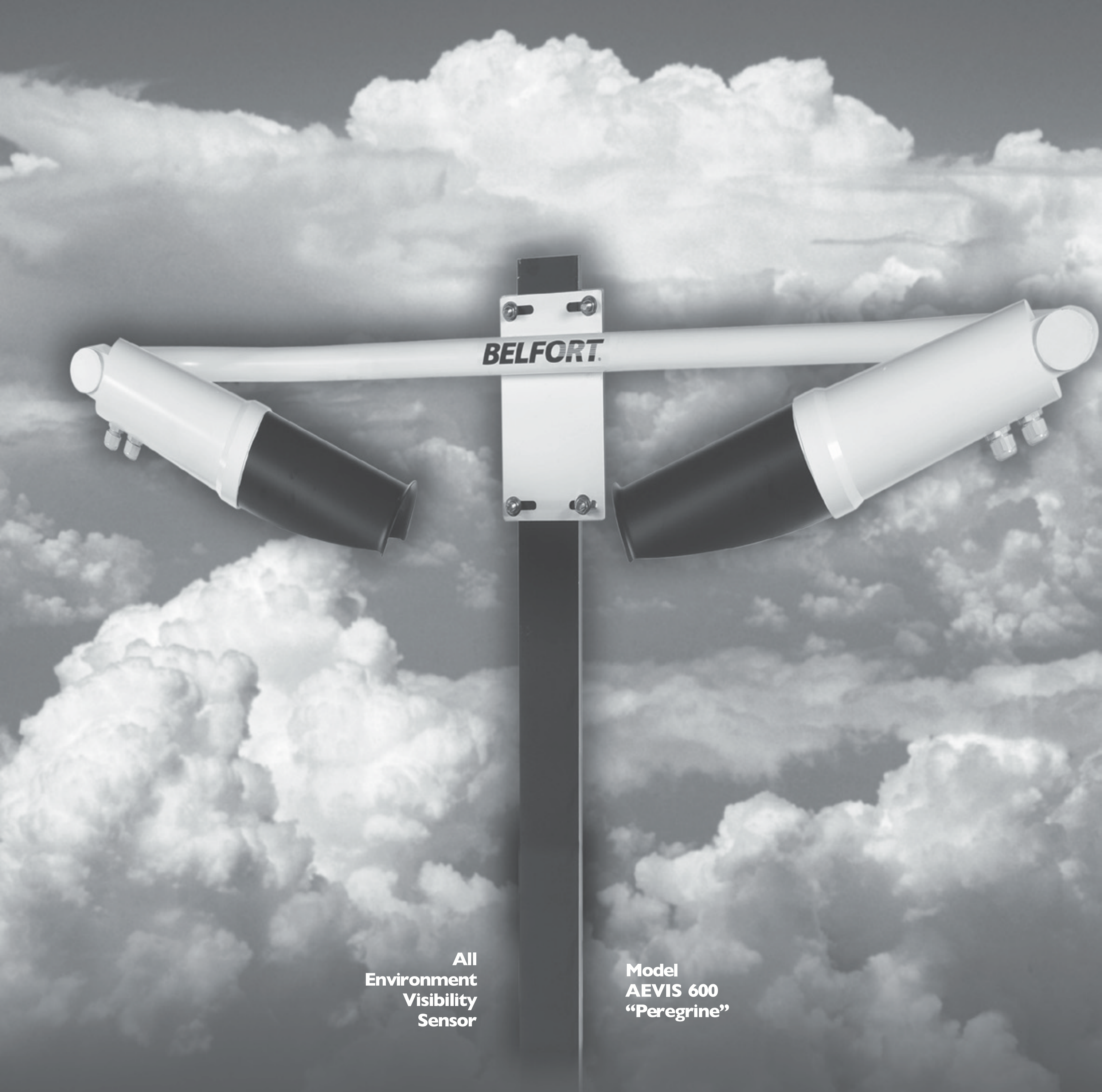
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