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Instruments that measure up!
Aerosol, cloud, precipitation, and their radiative properties are the largest source of uncertainty in predictions of climatic change and hamper the ability of numerical weather prediction models to forecast high-impact weather events. The Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) satellite mission aims to resolve these weaknesses by providing global profiles of cloud, aerosol, precipitation, and associated radiative properties using measurements made by four collocated active and passive sensors. For more information, see the article by Illingworth et al., starting on p. 1311. (Cover image: ESA)
NOWCAST

1221 NEWS AND NOTES
Past Changes in Climate Affected by Ocean Currents…For El Niño Predictions, Look to Pacific Winds… Does Pollen Help Form Clouds?… A Wave Discovery in the Magnetosphere

1227 PAPERS OF NOTE
A Parameterization of the Probability of Snow–Rain Transition… Better Spread-Error Relationship in a Multimodel Ensemble Prediction System

1229 REMOTE SENSING
CloudSat Observes a Labrador Sea Polar Low

DEPARTMENTS

1407 NEW MEMBERS
1410 CALENDAR OF MEETINGS
1414 CALL FOR PAPERS
1420 NOMINATION SUBMISSIONS
1422 CORPORATION AND INSTITUTIONAL MEMBERS
1426 PROFESSIONAL DIRECTORY
1431 INDEX TO ADVERTISERS
1432 PUBLICATION ORDER FORM

THE FRONT PAGE

RECENT HEADLINES ON THE AMS BLOG
http://blog.ametsoc.org

Summer Meeting Leads to Summer Tweeting
A New Web Vision
Is This Our Moonshot Moment?

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Golf is the ultimate weather game, and not because of rain delays and lightning hazards. The atmosphere, not the ground, is the course of play. The terrain is different every day, due to weather. Moisture impedes the roll of the ball and yet eases its flight. Rain clumps the turf and every shot must take wind into account.

Nearly every shot gives the ultimate pay-off: gravity’s rainbow. The golfer admires the ball’s heavenward charge and experiences momentary weightlessness as the outcome hangs in balance before the plunge back to earth. Witnessing the apex of a golf shot, I first sensed that air was something to be appreciated and studied for itself. Fascination with the arc of the ball presaged an interest in the pathways of air in thunderstorms.

The DC3 project described in this issue (p. 1281) evokes that visceral identification with rising and falling trajectories. The mystery is why the air going into a storm is so different than the air going out. The chemistry of the storm leaves an indelible imprint on the atmosphere.

But, speaking of trajectories, I felt a twinge of disillusionment reading Dacre et al. (p. 1243). Extratropical storms approaching a coastline can form long lines of vapor commonly called “atmospheric rivers.” These vapor streams take aim at a spot near a coastline and dump torrents of rain, seemingly with moisture from thousands of miles away. When you watch a golf ball land precisely where it is aimed, it is as if the air were traced by invisible guide wire. It looked like atmospheric rivers had that long-distance targeting power that duffers dream of and the pros seem to master.

However, Dacre et al. explain that an atmospheric river is not what it seems. It is a footprint of the weather system—a legacy of converging trajectories rather than transoceanic transport. The moisture is largely from within the area of the storm.

Science and golf alike are full of this type of disappointment. In science, neat metaphors eventually are torn apart by facts. Similarly, shot by shot, golfers get disabused of the fantasy that the ball will go where they aim it. The sooner you accept these realities the less disappointment you suffer.

The CESM project described in this issue (p. 1333) seeks this kind of reality check. It isolates the internal variability of the climate system from other changes and trends that such variability might mask. This is the eternal struggle of separating the good shots from the bad. Did the long grass turn the club at impact? Did the wind aloft shift? Variability is the bane of golf. All too often it is the golfer’s own inherent variability, but there are usually enough other variables that the reality of human inconsistency stays hidden.

Mastering climate variability has long been the pursuit of atmospheric science. The bond between scientists and golfers is that their long walk in nature is filled with disappointments, yet remains compelling and addictive. It sets the spirit soaring.

—Jeff Rosenfeld, Editor-in-Chief
airflow. Thus, water vapor in the cyclone’s warm sector, not long-distance transport of water vapor from the subtropics, is responsible for the generation of filaments of high water vapor content. A continuous cycle of evaporation and moisture convergence within the cyclone replenishes water vapor lost via precipitation. Thus, rather than representing a direct and continuous feed of moist air from the subtropics into the center of a cyclone (as suggested by the term “atmospheric river”), these filaments are, in fact, the result of water vapor exported from the cyclone, and thus they represent the footprints left behind as cyclones travel poleward from the subtropics. (Page 1243)

THE LATMIX SUMMER CAMPAIGN: SUBMESOSCALE STIRRING IN THE UPPER OCEAN

Lateral stirring is a basic oceanographic phenomenon affecting the distribution of physical, chemical, and biological fields. Eddy stirring at scales on the order of 100 km (the mesoscale) is fairly well understood and explicitly represented in modern eddy-resolving numerical models of global ocean circulation. The same cannot be said for smaller-scale stirring processes. Here, the authors describe a major oceanographic field experiment aimed at observing and understanding the processes responsible for stirring at scales of 0.1–10 km. Stirring processes of varying intensity were studied in the Sargasso Sea eddy field approximately 250 km southeast of Cape Hatteras. Lateral variability of water-mass properties, the distribution of microscale turbulence, and the evolution of several patches of inert dye were studied with an array of shipboard, autonomous, and airborne instruments. Observations were made at two sites, characterized by weak and moderate background mesoscale straining, to contrast different regimes of lateral stirring. Analyses to date suggest that, in both cases, the lateral dispersion of natural and deliberately released tracers was $O(1) \text{ m}^2 \text{ s}^{-1}$ as found elsewhere, which is faster than might be expected from traditional shear dispersion by persistent mesoscale flow and linear internal waves. These findings point to the possible importance of kilometer-scale stirring by submesoscale eddies and nonlinear internal-wave processes or the need to modify the traditional shear-dispersion paradigm to include higher-order effects. A unique aspect of the Scalable Lateral Mixing and Coherent Turbulence (LatMix) field experiment is the combination of direct measurements of dye dispersion with the concurrent multiscale hydrographic and turbulence observations, enabling evaluation of the underlying mechanisms responsible for the observed dispersion at a new level. (Page 1257)

THE DEEP CONVECTIVE CLOUDS AND CHEMISTRY (DC3) FIELD CAMPAIGN

The Deep Convective Clouds and Chemistry (DC3) field experiment produced an exceptional dataset on thunderstorms, including their dynamical, physical, and electrical structures and their impact on the chemical composition of the troposphere. The field experiment gathered detailed information on the chemical composition of the inflow and outflow regions of midlatitude thunderstorms in northeast Colorado, west Texas to central Oklahoma, and northern Alabama. A unique aspect of the DC3 strategy was to locate and sample the convective outflow a day after active convection in order to measure the chemical transformations within the upper-tropospheric convective plume. These data are being analyzed to investigate transport and dynamics of the storms, scavenging of soluble trace gases and aerosols, production of nitric oxides by lightning, relationships between lightning flash rates and storm parameters, chemistry in the upper-troposphere that is affected by the convection, and related source characterization of the three sampling regions. DC3 also documented biomass-burning plumes and the interactions of these plumes with deep convection. (Page 1281)

THE EARTH CARE SATELLITE: THE NEXT STEP FORWARD IN GLOBAL MEASUREMENTS OF CLOUDS, AEROSOLS, PRECIPITATION, AND RADIATION

The collective representation within global models of aerosol, cloud, precipitation, and their radiative properties remains unsatisfactory. They constitute the largest source of uncertainty in predictions of climatic change and hamper the ability of numerical weather prediction models to forecast high-impact weather events. The joint European Space Agency (ESA)–Japan Aerospace Exploration Agency (JAXA) Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) satellite mission, scheduled for launch in 2018, will help to resolve these weaknesses by providing global profiles of cloud, aerosol, precipitation, and associated radiative properties inferred from a combination of measurements made by its collocated active and passive sensors. EarthCARE
ABSTRACTS

THE COMMUNITY EARTH SYSTEM MODEL (CESM) LARGE ENSEMBLE PROJECT: A COMMUNITY RESOURCE FOR STUDYING CLIMATE CHANGE IN THE PRESENCE OF INTERNAL CLIMATE VARIABILITY

While internal climate variability is known to affect climate projections, its influence is often underappreciated and confused with model error. Why? In general, modeling centers contribute a small number of realizations to international climate model assessments [e.g., phase 5 of the Coupled Model Intercomparison Project (CMIP5)]. As a result, model error and internal climate variability are difficult, and at times impossible, to disentangle. In response, the Community Earth System Model (CESM) community designed the CESM Large Ensemble (CESM-LE) with the explicit goal of enabling assessment of climate change in the presence of internal climate variability. All CESM-LE simulations use a single CMIP5 model (CESM with the Community Atmosphere Model, version 5). The core simulations replay the twenty to twenty-first century (1920–2100) 30 times under historical and representative concentration pathway 8.5 external forcing with small initial condition differences. Two companion 1000+–yr-long preindustrial control simulations (fully coupled, prognostic atmosphere and land only) allow assessment of internal climate variability in the absence of climate change. Comprehensive outputs, including many daily fields, are available as single-variable time series on the Earth System Grid for anyone to use. Early results demonstrate the substantial influence of internal climate variability on twentieth- to twenty-first-century climate trajectories. Global warming hiatus decades occur, similar to those recently observed. Internal climate variability alone can produce projection spread comparable to that in CMIP5. Scientists and stakeholders can use CESM-LE outputs to help interpret the observational record, to understand projection spread, and to plan for a range of possible futures influenced by both internal climate variability and forced climate change. [Page 1333]

THE IITM EARTH SYSTEM MODEL: TRANSFORMATION OF A SEASONAL PREDICTION MODEL TO A LONG-TERM CLIMATE MODEL

With the goal of building an Earth system model appropriate for detection, attribution, and projection of changes in the South Asian monsoon, a state-of-the-art seasonal prediction model, namely the Climate Forecast System version 2 (CFSv2) has been adapted to a climate model suitable for extended climate simulations at the Indian Institute of Tropical Meteorology (IITM), Pune, India. While the CFSv2 model has been skillful in predicting the Indian summer monsoon (ISM) on seasonal time scales, a century-long simulation with it shows biases in the ocean mixed layer, resulting in a 1.5°C cold bias in the global mean surface air temperature, a cold bias in the sea surface temperature (SST), and a cooler-than-observed troposphere. These biases limit the utility of CFSv2 to study climate change issues. To address biases, and to develop an Indian Earth System Model (IITM ESMv1), the ocean component in CFSv2 was replaced at IITM with an improved version, having better physics and interactive ocean biogeochemistry. A 100-yr simulation with the new coupled model (with biogeochemistry switched off) shows substantial improvements, particularly in global mean surface temperature, tropical SST, and mixed layer depth. The model demonstrates fidelity in capturing the dominant modes of climate variability such as the ENSO and Pacific decadal oscillation. The ENSO–ISM teleconnections and the seasonal leads and lags are also well simulated. The model, a successful result of

will improve our understanding of cloud and aerosol processes by extending the invaluable dataset acquired by the A-Train satellites CloudSat, Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and Aqua. Specifically, EarthCARE’s cloud profiling radar, with 7 dB more sensitivity than CloudSat, will detect more thin clouds and its Doppler capability will provide novel information on convection, precipitating ice particle, and raindrop fall speeds. EarthCARE’s 355-nm high-spectral-resolution lidar will measure directly and accurately cloud and aerosol extinction and optical depth. Combining this with backscatter and polarization information should lead to an unprecedented ability to identify aerosol type. The multispectral imager will provide a context for, and the ability to construct, the cloud and aerosol distribution in 3D domains around the narrow 2D retrieved cross section. The consistency of the retrievals will be assessed to within a target of ±10 W m–2 on the retrievals will be assessed to cross section. The consistency of around the narrow 2D retrieved aero- sol type. The multispectral imager will provide a context for, and the ability to construct, the cloud and aerosol extinction and optical depth. Combining this with backscatter and polarization information should lead to an unprecedented ability to identify aerosol type. The multispectral imager will provide a context for, and the ability to construct, the cloud and aerosol distribution in 3D domains around the narrow 2D retrieved cross section. The consistency of the retrievals will be assessed to within a target of ±10 W m–2 on the (10 km)2 scale by comparing the multiview broadband radiometer observations to the top-of-atmosphere fluxes estimated by 3D radiative transfer models acting on retrieved 3D domains. (Page 1311)
Indo–U.S. collaboration, will contribute to the IPCC’s Sixth Assessment Report (AR6) simulations, a first for India. (Page 1351)

CLOUDS IN THE CLOUD: WEATHER FORECASTS AND APPLICATIONS WITHIN CLOUD COMPUTING ENVIRONMENTS
Cloud computing offers new opportunities to the scientific community through cloud-deployed software, data-sharing and collaboration tools, and the use of cloud-based computing infrastructure to support data processing and model simulations. This article provides a review of cloud terminology of possible interest to the meteorological community, and focuses specifically on the use of infrastructure as a service (IaaS) concepts to provide a platform for regional numerical weather prediction. Special emphasis is given to developing countries that may have limited access to traditional supercomputing facilities. Amazon Elastic Compute Cloud (EC2) resources were used in an IaaS capacity to provide regional weather simulations with costs ranging from $40 to $75 per 48-h forecast, depending upon the configuration. Simulations provided a reasonable depiction of sensible weather elements and precipitation when compared against typical validation data available over Central America and the Caribbean. (Page 1369)

In the July issue of BAMS, in the article “The Campaign on Atmospheric Aerosol Research Network of China: CARE-China” by Jinyuan Xin et al. (DOI:10.1175/BAMS-D-14-00039.1), the affiliation for author Xinming Wang was inadvertently omitted from the title page due to an editorial error. Dr. Wang’s affiliation is Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China.

“An engrossing account of New England’s worst natural catastrophe.”
— KERRY EMANUEL, Professor of Atmospheric Science, MIT

Taken by Storm, 1938:
A Social and Meteorological History of the Great New England Hurricane
LOURDES B. AVILÉS
When the Great New England Hurricane of 1938 hit the Northeast unannounced, it changed everything from the landscape, to Red Cross and Weather Bureau protocols, to the measure of Great Depression relief New Englanders would receive, and the resulting pace of regional economic recovery. The science behind this storm is presented here for the first time, with new data that sheds light on the motivations of the Weather Bureau forecasters. This compelling history successfully weaves science, historical accounts, and social analyses to create a comprehensive picture of the most powerful and devastating hurricane to hit New England to date.
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ICE CORE SHOWS OCEAN CURRENTS INFLUENCED CLIMATE CHANGES FROM POLE TO POLE

Thousands of years ago, during the Last Glacial Maximum, Greenland’s climate was extremely volatile, as a number of sudden and significant changes in mean average temperature occurred every few thousand years. A recent collaborative study of an exceptionally detailed ice core that involved 28 U.S. laboratories reveals that these changes were part of a global pattern that was primarily driven by ocean currents. The finding, published recently in Nature, could be helpful in enhancing global climate models.

Researchers utilized a unique ice-core analytical system to study a core taken from a site on the West Antarctic Ice Sheet (WAIS) that had “the best combination of thick ice, simple ice flow, and the right amount of annual snowfall,” according to the Desert Research Institute’s Kendrick Taylor, a coauthor of the paper. The WAIS Divide ice core contained information on a number of historical environmental conditions, including average ocean temperature, surface air temperature, wind patterns, and atmospheric greenhouse gas concentrations. The researchers analyzed more than two kilometers of the core for impurities related to sea salts and desert dust, and discovered that the pattern of sharp changes in climate, which first occurred around Greenland, would migrate to Antarctica in 200-year cycles. These climatic oscillations are known as Dansgaard-Oeschger events, and when such an event was in its warm phase in Greenland, temperatures would decrease in Antarctica around 200 years later; cold phases, which would cause temperatures in Greenland to plummet, would lead to warmer temperatures in Antarctica about 200 years afterward. The new study of the core revealed 18 such abrupt climate events over the past 68,000 years, and determined that the centuries-long time frame of each event’s migration pointed to an oceanic rather than atmospheric mechanism as the driver.

“The fact that temperature changes are opposite at the two poles suggests that there is a redistribution of heat going on between the hemispheres,” notes the study’s lead author, Christo Buizert of Oregon State University. “We still don’t know what caused these
past shifts, but understanding their timing gives us important clues about the underlying mechanisms.”

The scientists connected the changes to oceanic processes, because “[i]f [they] were propagated by the atmosphere, the Antarctic response would have occurred in a matter of years or decades, not two centuries,” explains Buizert. “The ocean is large and sluggish, thus the 200-year time lag is a pretty clear fingerprint of the ocean’s involvement.” He added that it is “very likely” that the Atlantic Meridional Overturning Circulation is connected to these abrupt climate variations.

“Past ice core studies did not reveal the temperature changes as clearly as this remarkable core,” says the University of Washington’s Eric Steig, a coauthor of the paper. “It is a major advance to know that the Earth behaves in this particular way.” [Sources: Desert Research Institute, Oregon State University]

**Connecting El Niño to Pacific Westerly Winds**

New research published in *Nature Geoscience* may shed light on the disappointing El Niño event of 2014–15. Originally projected to be a significant episode comparable to the strong El Niño of 1997–98, it instead was declared by the NWS in March to be a “weak” event—not to mention that it arrived months later than originally anticipated. The new study has found that protracted wind bursts that form in the western Pacific Ocean have a strong influence on the development and intensity of El Niño events.

By studying 50 years of data on tropical Pacific sea surface temperatures and westerly wind bursts, researchers found that “[t]he development of strong westerly winds in the central equatorial Pacific in association with the warming to its east appears to be an essential element of large El Niño events,” explains the University of Maryland’s Raghu Murtugudde, a coauthor of the study. For example, the 1997–98 El Niño—the strongest ever recorded—was preceded in May of 1997 by strong westerly winds in the western and central equatorial Pacific—winds that were not present last year.

The wind bursts are “intraseasonal—they’re not weather, they’re not climate, but somewhere in between,” according to Murtugudde. They can spur El Niño events by energizing Kelvin waves that generate warm surface waters in the eastern equatorial Pacific, and by producing powerful equatorial surface currents that extend the eastern edge of the equatorial Pacific warm pool.
Using an intermediate ocean–atmosphere coupled model that included the westerly wind bursts, the research team was also able to identify three “flavors” of El Niño:

1) extreme events with the greatest warming near the coast of South America, and with westerly winds in the western Pacific growing stronger and extending east of the dateline; 2) a grouping of weak warm events centered near the dateline; and 3) moderate warming in the central-eastern equatorial Pacific. When the models were run without the wind bursts, only one flavor was evident: the model output of a standard El Niño.

Taken together, the findings could be invaluable in improving future projections of ENSO events.

“Our study shows that the wind bursts are definitely having an effect,” Murtugudde says. “We better learn to predict them if we are going to have skillful El Niño predictions.”

[Source: University of Maryland]

STUDY LINKS POLLEN AND CLOUD FORMATION

Atmospheric scientists have largely ignored pollen in their research, believing that pollen grains were “too large to be important in the climate system, too large to form clouds or interact with the Sun’s radiation,” explains Allison Steiner of the University of Michigan. Additionally, “the large particles don’t last in the atmosphere,” she says, as...
“[t]hey tend to settle out relatively quickly.” But an investigation of pollen allergy literature revealed that “it’s pretty well known that pollen can break up into these tiny pieces and trigger an allergic response,” Steiner says. Her curiosity led her to investigate further, and she and colleagues discovered that pollen could have a much greater atmospheric influence than previously believed. She is the lead author of new research on the topic in Geophysical Research Letters.

In the United States, the majority of wind-driven pollen comes from ragweed and a variety of trees—oak, pecan, birch, cedar, and pine. The research team took two grams of pollen from each of those sources, soaked it in pure water for an hour, and utilized an atomizer to spray the moist pollen particles into a cloud-making chamber. According to Steiner, they discovered that “when pollen gets wet, it can rupture very easily in seconds or minutes and make lots of smaller particles that can act as cloud condensation nuclei, or collectors for water.”

By examining the particles with a scanning electron microscope, the researchers determined that the pollen grains had decreased in size from 20–50 micrometers to the nanometer range, which is an appropriate size for cloud formation. Specifically, they found that in the chamber, particles from all of the pollen sources that were 50, 100, or 200 nanometers in size had moisture collecting on them that spurred cloud formation.

The findings could be valuable in both climate and public health research, and the scientists involved in this study are next planning to go outside the lab to investigate in nature how pollen influences weather patterns.

“What happens in clouds is one of the big uncertainties in climate models right now,” Steiner says.

I don’t believe there is a major regime shift that’s protecting the U.S.”

—TIMOTHY HALL of the NASA Goddard Institute for Space Studies, commenting on the recent absence of major hurricanes to make landfall in the United States. As the 2015 season approached, it had been nine years since a Category 3 (or stronger) hurricane had reached the United States (Hurricane Wilma in 2005). Hall was lead author of a recent study in Geophysical Research Letters that examined the probabilities of such a hurricane gap. He and coauthor Kelly Hereid of ACE Tempest Reinsurance ran a computer model that included two indices of climate variation that can influence hurricane formation: North Atlantic sea surface temperatures and ENSO state. They conducted 1,000 simulations of tropical cyclones for the years 1950–2012 in order to estimate the statistical properties of periods without hurricane events. The models showed that a nine-year hurricane drought occurs once every 177 years, and that the average annual odds of at least one U.S. landfalling hurricane is 0.39—a bit more than one-in-three—with those odds having no connection to what happened in previous years. Ultimately, they found that the recent hurricane drought was largely due to “dumb luck,” according to Hall, rather than a specific phenomenon. They also discovered that the nine-year hurricane void was the longest since record-keeping began in 1851—surpassing an eight-year gap from 1861 to 1868. [SOURCES: blogs.agu.org, eenews.net]
new map documents worldwide lightning strikes

Two satellites have contributed data used to create a new map showing the frequency of lightning flashes across the globe. In this image, the map reveals that lightning strikes occur most commonly near the equator, and more often over land than over oceans. These patterns can be attributed to the absorption of sunlight by solid land, which heats up the land more rapidly than the water. This in turn increases the instability in the atmosphere, leading to intense lightning storms.

The image shows average yearly numbers of lightning flashes per square kilometer from 1995 to 2013, with the largest number of flashes indicated in bright pink (areas with fewer flashes are represented in gray and purple). The map reveals that the greatest number of lightning flashes in the world strike in the eastern Democratic Republic of the Congo, and over and around Lake Maracaibo in northwestern Venezuela. Other heavy-strike areas include Indonesia, the Himalayan Forelands, the Pampas of Argentina, and central Florida.

According to NASA’s Daniel Cecil, the new data used to create the map, which were taken from NASA’s TRMM satellite and the Orbview-1/Microlab satellite, are a significant benefit to global lightning research. “The longer record allows us to more confidently identify some of these finer details,” he explains. “We can examine seasonality and variability through the day and year-to-year.” [Source: NASA Earth Observatory]

radiation belts. This is important “because whenever…the magnetopause gets rattled [by the solar wind] it will create waves that propagate everywhere in the magnetosphere, which in turn can energize or deenergize the particles in the radiation belts,” explains Raeder. The changing energy levels can influence the belts’ capacity to protect technology on both spacecraft and Earth from the electromagnetically charged solar wind.

The ultra-low-frequency Kelvin-Helmholtz waves form from velocity shear—when one or multiple fluids interact at differing speeds, creating instability that manifests itself in breaking waves. [Source: University of New Hampshire]
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Knowledge of precipitation phase is critical for many atmospheric studies, including remote sensing of precipitation. For example, from the same value of observed radar reflectivity or a brightness temperature, a misclassification of hydrometeor phase can result in order-of-magnitude errors in the estimated precipitation rate. Therefore, an accurate determination of hydrometeor phase based on environmental variables is often needed before conducting precipitation retrievals. Our study aimed to determine how certain geophysical parameters affect precipitation phase, and then sought to...
develop a parameterization model that incorporates the significant geophysical parameters necessary to estimate the conditional probability of solid precipitation.

Using global ground-based observations over multiple decades, the influence of different geophysical parameters on precipitation phase is investigated. The parameters we studied were near-surface air temperature, atmospheric moisture, low-level (0–500 m) vertical temperature lapse rate, surface skin temperature, surface pressure, and land cover type. To combine the effects of temperature and moisture, wet-bulb temperature, instead of air temperature, was used as a key parameter for separating solid and liquid precipitation. Results show that in addition to wet-bulb temperature, vertical temperature lapse rate affects the precipitation phase. For example, at a near-surface wet-bulb temperature of 0°C, a lapse rate of 6°C km⁻¹ results in an 86% conditional probability of solid precipitation, while a lapse rate of −2°C km⁻¹ results in a 45% probability. For near-surface wet-bulb temperatures less than 0°C, skin temperature affects precipitation phase, although the effect appears to be minor. Results also show that surface pressure appears to influence precipitation phase in some cases; however, this dependence is not clear on a global scale. Land cover type does not appear to affect precipitation phase.

Based on these findings, a parameterization model has been developed that accepts available meteorological data as input, and returns the conditional probability of solid precipitation. The geophysical parameters included in the parameterization are near-surface temperature, relative humidity, low-level vertical lapse rate, surface skin temperature, and surface type (land or ocean). Because of the complicated relations between the solid precipitation probability and geophysical variables, the parameterization was implemented using look-up tables instead of analytical function forms. At a minimum, the near-surface (2 m) air temperature and surface type must be given, but a higher number of input variables results in a more accurate estimate.

A computer code that implements this parameterization model can be obtained from the authors at gliu@fsu.edu.—ELIZABETH M. SIMS (FLORIDA STATE UNIVERSITY) AND G. LIU, "A Parameterization of the Probability of Snow–Rain Transition,” in a forthcoming issue of the Journal of Hydrometeorology.

**Better Spread-Error Relationship in a Multimodel Ensemble Prediction System**

Ensemble forecasts using a single model, with initial conditions as diverse as is plausible given observation errors, are notoriously underdispersive. That is, nature (or verification) falls outside the ensemble range more often than it should by chance. As an Indo-US collaboration toward improving Indian monsoon prediction capabilities, a multimodel ensemble (MME) prediction system has been developed. To increase model diversity within the basic framework of the manageable model code, this MME uses a suite of different variants of the US NOAA NCEP Climate Forecast System (NCEP-CFSv2) and its atmosphere component, the Global Forecast System (GFS), with different resolutions, parameters, and coupling configurations (to address coupled SST biases), motivated by the different physical mechanisms thought to influence monsoon forecast errors in the extended range (10–20 day lead times). Based on performance experience, and aiming to maximize the operational skill depending on our available computer resources, we chose to pool 3 variants based on CFS: 11 members of CFST126 (~100 km), 11 members of CFST382 (~38 km), and 21 members of GFS forced with bias-corrected forecast SST from CFS. Evaluation of various skill measures suggests that this CFS-based Grand MME system known as CGMME is better than any participating single model ensembles (SMEs) in terms of 5-day average lead deterministic and probabilistic skill scores as well as its improved skill in predicting the large-scale monsoon intraseasonal oscillations (MISOS).

It is found that the CGMME provides multiple benefits: by encompassing the errors in both initial conditions and forecast model physics, it provides better probability forecasts from the users’ perspective (measured by increased reliability) along with skillful deterministic forecasts. Part of the overconfidence penalty involved in SMEs is overcome in the MME, improving the spread-error relationship, so that the MME approach adds value to both the deterministic and probabilistic forecast. This CGMME is shown to be better, both in deterministic measures of the ensemble mean forecast, and in probabilistic skill measures like spread-error relationships (which penalize overconfidence, the forecast face of model underdispersion). For clarity, users are provided with a single consensus forecast (the CGMME ensemble.

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**CGMME**

**PredIctIon SyStem**

**multImodel enSemble**

**CGMME**

**CGMME**
The Arctic oceans give birth to intense mesoscale low-pressure systems, usually generated by outbreaks of cold, dry polar air over warm water. These systems are called polar lows. The classical polar low is included as a subtype that is restricted to maritime systems with near-surface winds exceeding 15 m s\(^{-1}\). These types of polar lows can exhibit deep convection, a warm core, and lifetimes of a few hours to a few days. Sensible heat fluxes from the oceans play an important role in creating these systems, while latent heat fluxes can become important in their mature and decaying stage. They may appear visually similar to tropical cyclones on satellite imagery with an eyelike feature. Numerical simulations of polar lows are often unsuccessful. This can be due to poor initial and boundary conditions, model resolution, and the choice of cloud microphysical scheme. Due to their rapid genesis, small size, and occurrence over data-sparse oceans, polar lows pose a serious threat to mariners and coastal interests. Polar-orbiting satellite imagery could be culled to develop a useful database of polar lows, improving what we know about them and how they can be simulated.

**REMOTE SENSING**

**CLOUDSAT OBSERVES A LABRADOR SEA POLAR LOW**

*by John M. Forsythe and John M. Haynes*

The Arctic oceans give birth to intense mesoscale low-pressure systems, usually generated by outbreaks of cold, dry polar air over warm water. These systems are called polar lows. The classical polar low is included as a subtype that is restricted to maritime systems with near-surface winds exceeding 15 m s\(^{-1}\). These types of polar lows can exhibit deep convection, a warm core, and lifetimes of a few hours to a few days. Sensible heat fluxes from the oceans play an important role in creating these systems, while latent heat fluxes can become important in their mature and decaying stage. They may appear visually similar to tropical cyclones on satellite imagery with an eyelike feature. Numerical simulations of polar lows are often unsuccessful. This can be due to poor initial and boundary conditions, model resolution, and the choice of cloud microphysical scheme. Due to their rapid genesis, small size, and occurrence over data-sparse oceans, polar lows pose a serious threat to mariners and coastal interests. Polar-orbiting satellite imagery could be culled to develop a useful database of polar lows, improving what we know about them and how they can be simulated.
Unlike tropical cyclones, polar lows are not routinely identified and tracked in real time. Their occurrence in high latitudes at the limits of usable geostationary satellite imagery makes tracking difficult. To obtain cases for scientific studies, including the improvement of polar low representation in numerical weather prediction models, these systems must be manually identified and matched with coincident data. The Norwegian Sea Surface Temperature and Altimeter Synergy (STARS) project (http://polarlow.met.no/) has begun to detect and catalogue conditions that are favorable for polar low occurrence. The report of the 12th workshop of the European Polar Low Working Group in the September 2013 issue of BAMS provides an update on the latest polar low science.

Satellites are the primary tools used to observe polar lows, but a few aircraft studies have also been performed. The first aircraft lidar observations of a polar low were taken in 2008 over the Norwegian Sea, with highest cloud tops at 7 km. Since 2006, the NASA CloudSat satellite with a 94-GHz cloud radar and its companion lidar-carrying satellite CALIPSO have provided a new view of global clouds. CloudSat provides a nadir-only view of clouds with 240-m vertical resolution and 1.3-by-1.7-km horizontal resolution. A variety of science products—such as radar reflectivity and derived products including cloud liquid and ice water content, cloud bases and tops, and cloud classification—are available at www.cloudsat.cira.colostate.edu.

To aid in polar low identification, Cooperative Institute for Research in the Atmosphere (CIRA) resources were utilized to create a GOES-East infrared sector over the Labrador Sea with a 12-image loop updated at 3-h intervals. Criteria for manual identification and further examination of CloudSat products were first a classically appearing polar low during daylight, and then inspection of the CloudSat Quicklook imagery for an overpass in the vicinity. A promising polar low case was identified in the Labrador Sea on 30 November 2013. The MODIS true color image of the polar low at 1615 UTC is shown in Fig. 1, with the CloudSat ground track indicated. The polar low had deep convection in a 50 km-wide band, an eyelike clear region, and radiating bands of upper-level cirrus. The NOAA Rapid Refresh model analysis at 1600 UTC indicated 10-m wind speeds of 35–40 kt on the west side of the polar low, confirming the classical appearance in satellite imagery. Temperatures at 500 hPa were between –40° and –45°C, favorable for polar low formation.

The evolution of the polar low and CloudSat radar cross-section is shown in Fig. 2. Two Geostationary Operational Environmental Satellite (GOES) infrared 11-µm images at 1500 and 1800 UTC bounding the CloudSat overpass indicate the rapid development of

Fig. 2. Rapid evolution of the polar low at (a) 1500 UTC 30 Nov 2013 and (b) 1800 UTC in GOES-East infrared imagery. (c) CloudSat radar reflectivity profile superimposed on MODIS visible image at 1615 UTC 30 Nov 2013. The CloudSat track is indicated by the red line. Dashed brown lines are spaced 2 km vertically above sea level.
the polar low cloud shield. In Fig. 2c, the radar reflectivity cross section is overlaid on the MODIS visible image of the polar low. Reflectivity below 800 m is not plotted due to clutter from the surface. The highest reflectivity is in the 50 km-wide cloud band bordering the broken cloud to the south, with values of 20 dBZ. Radar-indicated cloud tops are 5 km, or at a pressure of about 500 hPa. The CALIPSO lidar also indicated highest cloud tops of approximately 5 km, indicating deep opaque clouds. Sloping returns from upper-level cloud streaming from the main polar low band occur north of 62°N.

It is likely that there are many more intersections of CloudSat and polar lows in the Arctic. Assuming a polar low diameter of 200 km at 60°N, a 24-h lifetime, and 40 polar lows per year in the Northern Hemisphere, about 5 polar lows per year should have coincident CloudSat/CALIPSO daytime overpasses. Since CloudSat data begins in 2006, this implies that about 40 daytime cases should be available to date. These cases would also be observed by the other sensors in the A-Train satellite formation with CloudSat. Collecting these cases into a CloudSat overpass database would be a useful endeavor. Such a database exists for tropical cyclones at the CloudSat website, and more than 350 CloudSat overpasses within 50 km of the tropical cyclone center have been identified to date. Such an effort applied to polar lows would help improve our understanding and modeling of these systems.

**FOR FURTHER READING**


HURRICANE PIONEER
Memoirs of Bob Simpson
Robert H. Simpson with Neal M. Dorst

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William B. Gail

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Dynamical Downscaling and Loss Modeling for the Reconstruction of Historical Weather Extremes and Their Impacts
A Severe Foehn Storm in 1925

by Peter Stucki, Stefan Bronnimann, Olivia Martius, Christoph Welker, Ralph Rickli, Silke Dierer, David N. Bresch, Gilbert P. Compo, and Prashant D. Sardeeshmukh

In many parts of the world, intense windstorms represent a major natural hazard, with potential damage to buildings, structures, or forested areas (Jackson et al. 2013; COMET 2014). High-resolution wind and impact data are needed to describe meteorological characteristics and impacts of windstorms. However, such datasets are sparse in Switzerland prior to around 1980, and simulations of storm-related losses mostly cover events from recent decades.

Here, we reconstruct a high-impact foehn storm (definition in AMS 2014) in the Swiss Alps that occurred on 15 February 1925, and we model the associated losses on a local scale. First, we analyze the weather event and the related impact patterns by traditional documentary means. Then, we feed dynamically downscaled wind fields of the Twentieth Century Reanalysis (20CR) ensemble dataset (Compo et al. 2011) into an open-source economic loss model (Bresch 2014) that sweeps this historical windstorm across present-day landscapes and human-built structures. Comparison between the documentary evidence and the model simulation indicates that high-resolution numerical modeling of windstorms and associated losses has the potential to enter an era that has hitherto been the province of environmental historians; and such modeling could extend far beyond the Alps and 15 February 1925.

At 0900 LT on that Sunday (0800 UTC), R. Streiff-Becker, a passionate meteorologist, looked through his binoculars toward the Alps from his home in uptown Zurich, Switzerland (see Fig. 1a for locations). He noticed a broadening strip of clear sky that approached the city and contained only a few, fast-traveling clouds. Simultaneously, the Alpine range vanished behind a massive cloud wall. Streiff-Becker spotted several impressive snow plumes over the foothill summits. Shortly thereafter, the forelands and Zurich were caught by surprisingly gusty foehn winds. In his home town of Glarus, which is situated in a north-south-oriented foehn valley, southerly winds had been fierce during the early morning hours, but had already weakened by 1000 LT (0900 UTC). Concurrently, strong drizzle had set in upwind of the Alpine divide, and 24-h precipitation amounts of nearly 200 mm had been observed.

**DOCUMENTARY WEATHER AND LOSS RECONSTRUCTION.** The foehn storm of 15 February 1925 ranks among the most hazardous windstorms in Switzerland since the mid-nineteenth century (Stucki et al. 2014). Substantial documentation is available on the associated damage (Fig. 1b). For instance, the Swiss Forestry Journal published approximate amounts of windfall timber per administrative region (Swiss cantons). A nationwide insurance report (by Lanz-Stauffer and Rommel in 1936)
Fig. 1. (top) Traditional reconstruction vs (bottom) numerical simulation of the (left) wind field and (right) associated damage/loss from the 15 Feb 1925 foehn storm over Switzerland. (a) Manual wind speed observations (colored arrows) at 0600 LT (0500 UTC), converted from half Beauforts. Ticks on the color bar give approximate wind speed in m s\(^{-1}\). The color scale is as in (c). Regions and localities (triangles) in Switzerland are as referred to in the text. The dashed line marks the x-axis in Fig. 3b; the box marks the region shown in Fig. 4. The hillshade is courtesy of swisstopo. (b) Reported amounts of windfall timber in cubic meters (light gray segments) and building losses in Swiss francs (dark gray segments) per canton. Red crosses indicate approximate locations of substantial damage as retrieved from newspaper reports. (c) Maximum surface wind gust speed during the historical foehn storm calculated from a weather prediction model at 3-km grid size between 0600 UTC on 13 Feb 1925 and 0800 UTC on 16 Feb 1925 (color shade). The direction of the 10-m instantaneous wind is shown for the time when winds were the most violent in Switzerland (vectors). (d) Simulated monetary loss in Swiss francs per km\(^2\) at municipality level under modern (year 2009) socioeconomic conditions related to the historical foehn storm (base-10 logarithmic scale). The monetary loss simulated for each municipality is normalized by the municipal area.

provided cantonal lists of building losses. Newspapers published dramatic eyewitness reports and roughly located the damage areas—mostly along the Alpine foreland of northeastern Switzerland and at foehn valley exits. Less damage was reported from the foehn valley heads and toward southwestern Switzerland.

Such documentary sources provide important information on the intensities and spatial footprints of historical high-impact windstorms (e.g., Lamb and Frydendahl 1991; Mass and Dotson 2010). These reports are also helpful for weather reconstruction, but need to be complemented with quantitative observations. The
Swiss Meteorological Institute (today Federal Office of Meteorology and Climatology MeteoSwiss) maintained a relatively small network of wind stations, where manual observations in half Beauforts were recorded three times per day. Figure 1a shows hurricane-force winds on Saentis summit in northeastern Switzerland at 0600...
LT (0500 UTC) on 15 February 1925. Gale-force winds were observed in southern to southwestern Switzerland, and strong winds were observed at three stations near Altdorf, all located in a typical foehn valley in central Switzerland. At 1200 LT (1100 UTC), winds increased markedly in Zurich, while weaker winds were observed around Altdorf (not shown).

Meteorologists of the time appreciated the meteorological peculiarities of foehn storms. Scientists had monitored such events since the mid-nineteenth century to establish and corroborate their diverging and sometimes heavily disputed theories of foehn dynamics (Seibert 2012), and Streiff-Becker hence documented the event meticulously. For instance, he drew a surface weather map for Saturday, 14 February 1925 (Fig. 2a). The Alps are situated between a depression over the British Isles and a high over southeastern Europe, and the large pressure gradient across the Alps forms a typical foehn nose. A secondary area of low pressure is located over the western Mediterranean Sea. The associated strong southerly winds turn to easterly approaching the Alps, while southwesterly winds prevail north of the Alps.

In summary, these traditional reconstructions deliver a useful and detailed description of the local wind regimes and damages. However, the hazard and loss information is subjective and incomplete. It does not meet the requirements of modern weather research or risk assessments.

Recently, the 20CR extended the temporal coverage of global atmospheric reanalyses back to 1871, allowing studies of historical weather based on today’s numerical and objective methods. The 20CR has proven to be reliable for analyzing synoptic-scale, midlatitude weather systems (Brönnimann et al. 2012; Stucki et al. 2012; Trigo et al. 2014). Going one step further, Michaelis and Lackmann (2013) reconstructed the New England Blizzard of 1888 using the numerical Weather Research and Forecasting model (WRF; Skamarock et al. 2008) to downscale from 20CR input to a 6-km horizontal grid.

DYNAMICAL DOWNSCALING. Here, we extend these latest methods with a modeling chain that allows reassessing the high-impact foehn storm of 15 February 1925 on synoptic to mesogamma scales.

The 20CR sets the boundary conditions for the high-resolution downscaling. For this, we use the ensemble mean of the global 56 ensemble member fields, available on a 2° × 2° latitude-longitude grid (grid spacing of approximately 200 km over Central Europe) every 6 h.

In the reanalysis, a deep surface low is located over Great Britain and surface air pressure increases toward southeastern Europe at 0000 UTC on 15 February 1925 (Fig. 2b). Mean sea level pressure (MSLP) differences across the Alps are approximately 5.5 hPa (20CR ensemble range 3–6.5 hPa, not shown). A very strong southerly flow extends from the Sahara to the Alps, but wind speeds north of the Alps are rather low. It is evident that the 20CR can resolve the large-scale flow, but the foehn nose and the potential area of low pressure over the Mediterranean in Fig. 2a are not accentuated in the 20CR. The 2-degree grid of the 20CR is too coarse to realistically represent the complex topography of the Alps, and hence fails to capture wind systems that are strongly influenced by this factor.

To compensate, we employ dynamical downscaling for a closer look at the Alpine region. 20CR ensemble mean fields (and the 20CR ensemble members #27 and #51, see Footnote 1) provide the initial and lateral boundary conditions that drive the regional, higher-resolution WRF model (version 3.3.1) for a limited domain over Europe. Two more refinement steps result in three domains. Horizontal grid spacing decreases from 45 km in the largest domain to 9 km in the intermediate to 3 km in the smallest domain, which covers Switzerland and adjacent regions. The vertical structure of the atmosphere is described using 31 vertical layers.2 Hourly model output is used for the analysis. The simulation starts at 0600 UTC.

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1 During the foehn storm, the 20CR ensemble standard deviation of mean sea level pressure (MSLP) remains small over Europe (≤1.2 hPa; cf. Fig. 2b), indicating a small range of probable initial conditions. Over most of the same period, the two members related to the highest (#27) and lowest (#51) wind speeds over Switzerland differ by 0.5–1.5 hPa in the MSLP field (not shown). At 0000 UTC on 15 February 1925, the ensemble mean and member #27 produce similar pressure gradients across the Alps (5.5 hPa and 6 hPa), whereas #51 is an outlier, concomitant with the lowest pressure gradient across the Alps (3 hPa, Fig. 2b). Accordingly, selected information from the downscaled members #27 and #51 provides evidence of a more probable versus an outlier simulation over the core period of the foehn storm (see text).

2 Turbulence is calculated by using the Mellor–Yamada scheme and the surface layer is parameterized according to the Monin-Obukhov scheme. The microphysics scheme by Lin et al. (1983) is used together with the RRTM scheme for longwave and the Dudhia scheme for shortwave radiation.
on 13 February 1925 (the lead time of >1 day allows small-scale atmospheric features to spin up) and ends at 0800 UTC on 16 February 1925.

**HIGH-RESOLUTION NUMERICAL SIMULATION: METEOROLOGY REVISITED.**

Next, we analyze the main meteorological features in the 45-km WRF domain at 0400 UTC on 15 February 1925 (Fig. 2c). Reportedly, this is the time when the first intense foehn phase occurred. At the 300-hPa level, there is an elongated trough over Western Europe, and wind speeds of up to 65 m s⁻¹ in the downscaled ensemble mean (denoted DEM hereafter; 65 m s⁻¹ in member #27, 60 m s⁻¹ in #51, not shown) indicate the presence of the jet stream over Central Europe. The Alps are on the anticyclonic
side of the jet maximum. In the right-front quadrant of the jet, subsidence increases the stability aloft, and this in turn supports the strengthening of downslope winds at the surface (Jackson et al. 2013; COMET 2014).

At the same time, topographically induced modulations of the surface pressure field become gradually more apparent in the 45-km and 9-km domains (Figs. 2c and 2d), and typical mesoscale foehn features emerge. In Fig. 2d, MSLP contours delineate the foehn nose, and minimum MSLP values near 990 hPa are found in the foehn regions, which results in a pressure difference of approximately 16 hPa in the DEM (14 hPa in #27, 6 hPa in #51) across the Alps. This agrees well with a difference of 12 hPa between Basel (northern Switzerland) and Lugano (southern Switzerland; reported in the Annals of the Swiss Meteorological Institute), and with Streiff-Becker’s weather chart (Fig. 2a). As in the 20CR, the secondary area of low pressure over the central Mediterranean is not very accentuated. For 1925, MSLP assimilation in the 20CR is based on a relatively dense network in the Mediterranean area (see ISPD 2014) and the 20CR ensemble standard deviation is small (≤1.2 hPa, c.f. Fig. 2b). In Fig. 2a, the wind vectors south of France are rather inconsistent with the pressure field, but in agreement with the 20CR and the WRF output (Figs. 2b–d). This points to the lobe over the Mediterranean in Streiff-Becker’s conceptual chart being exaggerated. Except for this region and a secondary low over Belgium, the downscaled surface wind field (Fig. 2d) agrees well with the historic weather chart, and strong surface winds prevail across the Alps. Warm spots of around 15°C in the DEM (15°C in #27, 8°C in #51, not shown) are found along the north side of the Alps (Fig. 2d). This corresponds with reports of 17°C on higher grounds in the foehn regions at 0700 LT (0600 UTC).

Streiff-Becker’s conceptual cross section of the wind field through Glarus on 15 February 1925 shows further interesting features of the foehn storm (Fig. 3a). A very strong southerly flow (25–35 m s⁻¹) advepts precipitating clouds across the Alps, causing so-called dimmer (dimmed daylight) in the Glarus valley. Here, surface winds can be turbulent, and even weak northerlies are observed. The actual, very strong foehn winds touch the surface farther north in the Alpine forelands near Lake Zurich. Farther downstream, they are lifted over a shallow layer of colder air, wherein a weak reverse flow persists.

A similar perspective emerges from the high-resolution simulations (Fig. 3b) for 0400 UTC on 15 February 1925. Shown is a south-north cross-section through the 3-km model domain (i.e., across the Alpine divide and through Altdorf). This section is parallel to Fig. 3a; it was chosen because the topography is closer to single-range mountains used in idealized flow simulations than at Glarus.
Decreasing spacing of the isentropes between the surface and the midtroposphere indicates increasing atmospheric stability on the upwind side of the mountain top (lapse rates of 5–6°C km⁻¹, not shown). The cross-barrier flow is very strong in the DEM (>30 m s⁻¹, ≥28 m s⁻¹ in #27, ≥20 m s⁻¹ in #51, not shown), and wind speed generally increases with height. Relative humidity at lower levels exceeds 90% (Fig. 3b). This is a “textbook” deep foehn situation with forced moist-adiabatic ascent of air and associated heavy precipitation on the southern side of the Swiss Alps (Richner and Hächler 2013).

Downwind of the mountain barrier, relative humidity decreases rapidly, indicating the foehn wall and subsequent clear sky. The changing atmospheric stability and the complex terrain produce a flow with many typical features of a mountain wave (Markowski and Richardson 2010; Jackson et al. 2013; Richner and Hächler 2013; COMET 2014). Tightly spaced, downward-sloping isentropes follow a tongue of very strong low-level winds in the DEM (>40 m s⁻¹, label A downward-sloping isentropes follow a tongue of very strong low-level winds in the DEM (≥30 m s⁻¹; ≥28 m s⁻¹ in #27, ≥20 m s⁻¹ in #51, not shown), and wind speed generally increases with height. Relative humidity at lower levels exceeds 90% (Fig. 3b). This is a “textbook” deep foehn situation with forced moist-adiabatic ascent of air and associated heavy precipitation on the southern side of the Swiss Alps (Richner and Hächler 2013).

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Loss Simulation: Historical Storm Over Modern Landscapes. The generally accurate and dynamically consistent wind fields from WRF output provide an encouraging basis for modeling the storm-related losses. High damage is typically related to maximum wind gusts (e.g., Klawa and Ulbrich 2003). Therefore, wind gust speeds from standard WRF postprocessing were used for impact modeling instead of the instantaneous wind speed values considered so far; the latter correspond approximately to 10-min values. With our approach, we model the potential economic losses from the 15 February 1925 foehn storm using present-day asset distributions in Switzerland. The economic losses are estimated at the municipality level, based on the field of the maximum downscaled surface wind gust speeds over Switzerland during the event (Fig. 1c).
and the probabilistic damage assessment module of the climate adaptation model (climada3; Bresch 2014; Reguero et al. 2014). In the climada model, we prescribe a modern (i.e., 2009) population distribution, assuming assets of 250,000 Swiss francs per inhabitant. For each municipality, the monetary damage is simulated based on the product between the respective asset value and a nonlinear damage function. This function (derived by Schwierz et al. 2010) relates the damage of a particular asset to the incurring wind gust at this location.

The model simulates high losses in northeastern Switzerland as well as in some regions of the Alps (Fig. 1d), where the wind gusts reach high values (Fig. 1c). In addition, metropolitan areas are recognizable in Fig. 1d, indicating that simulated storm losses are related to the distribution of both asset values and hazardous wind speeds.

In general, the pattern of simulated losses corresponds well with the pattern of reported losses associated with the foehn storm (Fig. 1b; slightly to moderately lower damage using #27 and #51, not shown). In particular, the damage locations between Altdorf and Glarus, around Lake Zurich and Saentis, are very well reproduced in the simulation, and even some damage areas in the Alpine foreland are well collocated with the reconstruction. However, we have very few to no damage reports from some areas with simulated losses, such that metropolitan areas are possibly overrepresented in the damage pattern. Such discrepancies could partly be due to nonreporting of losses from more remote areas (e.g., from southwestern Switzerland). Indeed, catastrophic precipitation and avalanches in southern Switzerland dominated the news from this region. Furthermore, we prescribed today’s distribution of asset values in Switzerland in the climada loss model. These values have changed considerably since 1925.

A further limitation may come from modeling losses at the municipality level: wind gust speeds, which are usually high on mountain tops, are combined with assets, which are typically high at valley bottoms.

LESSONS FROM THE EXPLORATORY ANALYSIS. We have shown that the downscaling and loss modeling chain enables the numerical, local-scale simulation of an extreme windstorm in the early twentieth century, and hence enables assessing potential harm from historical natural hazards in today’s (and possibly a future) world.

WRF-downscaling of the 20CR produces realistic wind fields on smaller scales and over complex terrain, although there are limitations regarding the exact location, intensity, and timing of the wind maxima. Our analyses of the 20CR ensemble mean, the 20CR ensemble members, and the three WRF simulations (DEM, #27, and #51) indicate that the 20CR ensemble mean and the DEM are suitable estimates of the initial and local-scale atmospheric conditions for this historical foehn storm. Nevertheless, our WRF simulations represent only three possible realizations of a very complex event, and there remain many opportunities to improve the simulation configuration. For instance, using all 56 ensemble members of the 20CR could provide an uncertainty estimation of our findings. Additionally, different gust parameterization schemes or a further spatial refinement of the simulations to a few hundred meters grid size and with an increased number of vertical levels should be tested in future work. The climada model output reflects the spatial distribution of reported impacts satisfactorily. However, refining the damage function in the model is necessary for more quantitative analyses.

We have also shown that historical expert concepts, reports, and sparse observations still remain valid and are very valuable sources for weather and impact reconstruction. We therefore advocate a complimentary use of both traditional and numerical techniques. Besides detailed case studies of historical events, our approach facilitates statistical or dynamical analyses of meaningful sample sizes (e.g., of extreme impacts at centennial time scales). It may break new ground for applications that require high-resolution, consistent, and long-term data coverage. In this sense, these novel opportunities for numerical simulations may well change our perspectives on historical high-impact weather.

FOR FURTHER READING


COMET, cited 2014: Mountain waves and downslope winds. [Available online at www.meted.ucar.edu/mesoprim/mtnwave/]


ISPD, cited 2014: The International Surface Pressure Databank. [Available online at www.esrl.noaa.gov/psd/data/ISPD/]


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HOW DO ATMOSPHERIC RIVERS FORM?

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Identifying the source of atmospheric rivers: Are they rivers of moisture exported from the subtropics or footprints left behind by poleward traveling storms?

Studies of heavy precipitation occurring in the winter over land in the midlatitudes have found that these events are almost always associated with extratropical cyclones (Lackmann and Gyakum 1999; Viale and Nunez 2011; Hawcroft et al. 2012). These heavy precipitation events often occur when warm moist air, located in the cyclone’s warm sector, encounters orography (e.g., along the west coast of the United States or United Kingdom), resulting in significant precipitation enhancement (Hand et al. 2004; Ralph et al. 2004; Neiman et al. 2008). These events involve a combination of large-scale synoptic and mesoscale processes in an orographic precipitation-enhancement mechanism known as the seeder–feeder mechanism (Bader and Roach 1977). In this process, precipitation from the cyclone’s upper-level cloud features (seeder clouds) falls through a lower-level mesoscale orographic stratus cloud (feeder cloud) capping a hill or small mountain and thus producing greater precipitation on the hill under the cap cloud than on the nearby flat land. While this mechanism does not change the total cyclone associated precipitation greatly, it can act to redistribute the precipitation and concentrate it over regions of orography. The effectiveness of the process depends on sufficiently strong low-level moist flow to maintain the cloud water content in the orographic feeder cloud and the continuing availability of precipitation from the seeder cloud (Hill et al. 1981; Browning 1990). In particular, moist air masses at levels below 1 km have been found to be critical to the moisture convergence associated with orographic precipitation enhancement in the coastal mountains of the western United States and United Kingdom (Smith et al. 2010; Neiman et al. 2011).

One common method for identifying these warm, moist low-level air masses is to detect filaments of high total column water vapor (TCWV) extending from the subtropics using satellite data. These 2D filamentary structures suggest long-distance, riverlike moisture transport and are routinely used as a proxy for identifying regions of strong water vapor transport (atmospheric rivers). High TCWV and strong low-level winds in the pre–cold frontal region lead to intense poleward moisture transport (Ralph et al. 2004, 2013) and have been associated with flooding in the United States and United Kingdom (Lavers et al.)
Trajectory case studies, however, have shown that atmospheric rivers do not represent true trajectories of water vapor transport (Bao et al. 2006). Rather, they depict the instantaneous position of corridors of enhanced water vapor in the portion of an extratropical cyclone known as the warm conveyor belt (Harrold 1973), which occurs near the leading edge of the cold front.

In a 23-year climatology of tropical moisture export, Knippertz and Wernli (2010) showed that trajectories that start south of 35°N largely recirculate toward the low latitudes before reaching the extratropics. Thus, while long-range transport of moisture from southerly latitudes can increase during atmospheric river events, the majority of precipitation in the extratropics is due to moisture evaporating at local or nearby latitudes (Sodemann and Stohl 2013). Any tropical moisture transport that does reach the extratropics appears to occur above the boundary layer and thus contributes to midlevel moisture (Knippertz and Martin 2007; Sodemann and Stohl 2013). Thus, although high TCWV bands appear to move and extend eastward in satellite animations, their leading ends are actually the manifestation of moisture convergence associated with warm conveyor belts that move with the extratropical cyclone (Bao et al. 2006; Cordeira et al. 2013).

To further elucidate the physical processes responsible for high TCWV band formation, Boutle et al. (2010) performed idealized modeling of an extratropical cyclone. They found that moisture is evaporated from the sea surface and transported large distances within the boundary layer toward the base of the warm conveyor belt airflow. Horizontal divergence forced by boundary layer drag and large-scale ageostrophic flow transports moisture away from these regions, which maintains the saturation deficit, allowing strong evaporation to be maintained. This is a continual process occurring throughout the life cycle, ensuring that the base of the warm conveyor belt airflow always contains moisture (Boutle et al. 2011). Thus, rather than consuming water vapor in preexisting high TCWV bands, as suggested by Zhu and Newell (1998), individual cyclones contribute to the formation and maintenance of high TCWV bands at the leading end by adding moisture accumulated ahead of their cold fronts (Bao et al. 2006; Sodemann and Stohl 2013).

Despite this, much published work on atmospheric rivers continues to assert that atmospheric rivers achieve their high water vapor content through direct transport from the tropics (e.g., Rivera et al. 2014; Rutz et al. 2014; Neiman et al. 2013; Wick et al. 2013; Dettinger 2013; Matrosov 2013; Guan et al. 2013; Kim et al. 2013; Moore et al. 2012). In this paper, we aim to illustrate the intrinsic role that extratropical cyclones have in atmospheric river formation. The misconception that moisture filaments are drawn into developing cyclonic circulations and that atmospheric rivers deliver large masses of warm, moist air directly from the tropics to the extratropics are addressed. Finally, use of the term “atmospheric river” as a suitable descriptor of these moist airflows is discussed.

In this paper, we will perform a kinematic analysis of the properties of a climatology of 200 extratropical cyclones and quantify the relative contribution of different processes leading to the formation of high TCWV bands in the atmosphere. This is achieved by calculating the water vapor budget for each cyclone in a frame of reference that moves with the cyclone. This allows us to determine how processes leading to the formation of atmospheric rivers evolve as the cyclone develops. Furthermore, tracking the cyclones relative to their time of maximum intensity allows us to composite the water vapor budget for a whole climatology of cyclones and thus generalize our results beyond individual case studies. This analysis quantifies in reanalysis data the role played by different aspects of the flow within extratropical cyclones in generating the features commonly identified as atmospheric rivers. It does not attempt to explain the dynamics of extratropical cyclones that generate the flows we have analyzed. For example, we consider the contribution of the horizontal convergence of the wind to the overall moisture convergence; this is equivalent to the role of vertical motion, which both generates and is enhanced by latent heating associated with cloud processes. Such feedback-driven enhancement is included in our analysis but is not isolated as a separate factor.

**METHOD.** Cyclone tracking and dataset. Following the work of Catto et al. (2010), we apply an objective cyclone identification and tracking algorithm (Hodges 1995) to fields from the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim) for the winter periods (December–February) of 1989–2009 (Dee et al. 2011). The temporal resolution of the data is 6 hourly. Tracks are identified using the 850-hPa relative vorticity truncated to T42 resolution (approximately 2.8°) to emphasize the synoptic scales. The 850-hPa relative vorticity features have been filtered to remove stationary cyclones (traveling <1000 km during their lifetimes) or short-lived cyclones (lifetimes < 48 h). Evaluation of the tracking algorithm, for a subset of the individual cyclones studied in this paper using high-resolution satellite data, can be found on the Extratropical
Cyclone Atlas (www.met.rdg.ac.uk/~storms). Dacre et al. (2012) (their Fig. 1) show the 200 most intense, in terms of the T42 vorticity, winter cyclone tracks with maximum intensity in the North Atlantic (70°–10°W, 30°–90°N), which are used in this paper. The tracks have significant poleward motion with an average meridional displacement of 20.3°N. The required fields are extracted from the ERA-Interim dataset along the tracks of the selected cyclones within a 1500-km radius surrounding the identified cyclone position on constant pressure surfaces.

**Water vapor budget.** To determine the relative importance of processes leading to the formation of high TCWV bands in the atmosphere, we calculate the individual terms in the water vapor budget for each gridbox column within the cyclone system (defined here as a region within 1500 km of the cyclone center). The cyclone center is defined as the location of the maximum 850-hPa relative vorticity value. The water vapor budget in a column of air is given by

\[ P - E = -\frac{1}{g} \int_{p_{500}}^{p} \partial q / \partial t \, dp - \frac{1}{g} \int_{p_{500}}^{p} \nabla \cdot (qu) \, dp, \]

where \( P \) is the surface precipitation flux (kg m\(^{-2}\) s\(^{-1}\)), \( E \) is the surface evaporation flux (kg m\(^{-2}\) s\(^{-1}\)), \( g \) is the acceleration due to gravity (m s\(^{-2}\)), \( q \) is the specific humidity (kg kg\(^{-1}\)), \( t \) is time (s), and \( u \) is the horizontal wind vector (m s\(^{-1}\)). Terms on the right-hand side of the equation are integrated from the surface to 500 hPa as water vapor transport above 500 hPa is found to contribute only a small amount (~1%) to the gridbox total, reflecting the decrease in specific humidity with height. Accumulated precipitation (P) and evaporation (E) are not available as analyzed fields in ERA-Interim and are therefore taken from short-range forecast accumulations. The ERA-Interim forecast estimates have previously been found to well correspond to gridded gauge data (Simmons et al. 2010) and to the Global Precipitation Climatology Project (GPCP) combined satellite and rain gauge product (Hawcroft et al. 2012). During the first hours of the forecast simulation, the precipitation field is affected by spinup. Given the requirement to have 6-hourly accumulations centered on 0000, 0600, 1200, and 1800 UTC, the forecast periods utilized in this study are accumulations from 9 to 15 h and from 15 to 21 h for forecasts starting at 1200 UTC the previous day and from 9 to 15 h and from 15 to 21 h for forecasts starting at 0000 UTC the same day. Recent work indicates that the lead time used in this paper offers the best estimates available from ERA-Interim given the 6-hourly accumulations required for this study (de Leeuw et al. 2015). All other fields are analyzed as described in Dee et al. (2011).

The first term on the right-hand side of Eq. (1) represents the vertically integrated rate of change of water vapor in the column \( dq/dt \). The second term on the right-hand side of Eq. (1) represents the vertically integrated divergence of water vapor from the column. Usually the negative of the second term is used and commonly referred to as the moisture flux convergence (MFC\(_{\text{TOT}}\)). The moisture flux convergence term in Eq. (1) can be split into two parts,

\[ -\frac{1}{g} \int_{p_{500}}^{p} \nabla \cdot (qu) \, dp = -\frac{1}{g} \int_{p_{500}}^{p} u \cdot \nabla q \, dp - \frac{1}{g} \int_{p_{500}}^{p} q \nabla \cdot u \, dp. \]

The first term on the right-hand side of Eq. (2) represents the vertically integrated horizontal advection of water vapor (MFC\(_{\text{ADV}}\)), and the second term represents the vertically integrated water vapor–weighted mass convergence (MFC\(_{\text{CONV}}\)). This term, of course, could also be written in terms of the water vapor–weighted vertical mass flux. In this paper, we will refer to these terms as the advection and mass convergence terms.

**CASE STUDY: 1 FEBRUARY 2002. Synoptic evolution.** To demonstrate the processes leading to the spatial distribution and transport of water vapor in extratropical cyclones, we first present the results for an example cyclone that caused flooding in the United Kingdom on 1 February 2002.

Figure 1 shows the track of an intense extratropical cyclone as it traveled northeastward from its genesis location in the North Atlantic to its lysis location in the Barents Sea. As it passed to the west of the United Kingdom, heavy precipitation associated with the cyclone between 0600 and 1200 UTC 1 February 2002 led to flooding in south Wales and Cumbria (regions of orography on the west coast of the United Kingdom). During this period, the cyclone was in its developing stage, reaching its highest 850-hPa vorticity value just south of Iceland.

Figure 2a shows the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) infrared satellite image of the cyclone at 0600 UTC 1 February 2002 (~12 h on cyclone track; Fig. 1). At this point in the cyclone’s evolution, the cloud structure has developed into a spiral-shaped pattern, with high-level cold cloud (bright white on image) wrapping cyclonically around the low pressure minima at the center of the figure (933 hPa; Fig. 2b).
Fig. 1. Track of a cyclone that passed to the west of the United Kingdom between 0600 UTC 31 Jan and 0600 UTC 4 Feb 2002. Gray labels show the location of the cyclone at 12-hourly intervals, relative to its time of maximum 850-hPa relative vorticity (0 h). Image is from the Extratropical Cyclone Atlas (www.met.rdg.ac.uk/~storms).

The cloud head is positioned along the boundary of two air masses, as represented by the occluded front in Fig. 2b, and the polar front cloud band is observed positioned parallel to the surface cold front. Scattered convective cloud can be seen in the air behind the cold front, where cold air is advected over a relatively warm sea surface resulting in convective instability.

Beneath these cloud features are regions of precipitation. Figure 2c shows the ERA-Interim forecast 6-hourly accumulated precipitation at the surface (centered at 0600 UTC 1 February 2002). The precipitation pattern shows a similar spiral shape to the cloud features. Over this time the heaviest precipitation (>6 mm (6 h)\(^{-1}\)) is located beneath the cloud head along the occluded front.

TCWV is a measure of the total amount of water vapor in the atmosphere. Figure 2d shows the instantaneous ERA-Interim TCWV. The highest values of TCWV are found in the cyclone's warm sector (bounded by the warm and cold fronts). A region of heavy precipitation beneath the polar front cloud band at the southernmost end of the cold front is found within the region of high TCWV air. Another region of heavy precipitation occurs along the occluded front close to the center of the cyclone and outside the region of high TCWV air. Thus, high TCWV is not a sufficient condition for heavy precipitation to occur. A column of air may have large absolute values of TCWV but not be saturated since higher temperature implies higher saturation vapor pressure. (The Clausius–Clapeyron equation, which determines the water-holding capacity of the atmosphere, predicts an increase of 7% for every 1°C rise in temperature.)

Figure 2e shows the instantaneous column-integrated saturation, calculated using ERA-Interim TCWV and temperature fields. High values of column saturation (>60%) are not restricted to the warm sector but extend across the warm frontal boundary, wrapping around the cyclone center. The column-integrated saturation shows a close correspondence with the cloud field pattern (Fig. 2a). Figure 2f shows the 500–300-hPa divergence field overlaid with 300-hPa wind speed isotachs. These fields give an indication of the large-scale environment in which the cyclone is developing. The cyclone is located in the left exit region of an upper-level jet, a favorable location for cyclogenesis, beneath a region of strong upper-level divergence.

Spatial distribution and magnitude of precipitation. In this section the spatial distribution and magnitude of precipitation and integrated water vapor transport (IVT) during the intensifying stage of the cyclone evolution is described. Figures 3a–c show the 6-hourly accumulated precipitation at three times during the development stage of the cyclone's evolution. Also shown in Figs. 3a–c are the positions of the surface cold, warm, and occluded fronts, plus the approximate location of the United Kingdom. The cyclone leading to precipitation and flooding in the United Kingdom
on 1 February 2002 is a secondary cyclone (labeled “2”) forming on the trailing cold front of a preexisting primary cyclone (labeled “1”). Cyclone 2 is located in the eastern North Atlantic 24 h before maximum intensity. Cyclones with genesis in the east Atlantic are often rapidly developing secondary cyclones, with a strong diabatic component (Gray and Dacre 2006; Dacre and Gray 2009, 2013). Cyclone 1 is in its mature stage of development and is beginning to dissipate (as described in the 1 February 2002 case study section above). Both cyclones 1 and 2 are associated with high IVT values located ahead of and parallel to the respective cyclone’s cold front (Fig. 3d). The 250 kg m⁻¹ s⁻¹ IVT contour is shown for comparison with papers such as Rutz et al. (2014), which uses this threshold to define atmospheric rivers. In this paper, we have not used this threshold to delineate atmospheric rivers since, for this case study, the threshold identifies a region that encompasses both the narrow band of high IVT and the broader warm conveyor belt region, and as such the atmospheric river is not a subset of the warm conveyor belt (as suggested in the literature) but a much broader region. Figure 3b shows cyclone 2’s location 12 h later. It is now located closer to the United Kingdom and is more wrapped up, with a longer occluded front and a narrower warm sector. Again, high IVT values are found in the cyclone’s warm sector (Fig. 3e). However, it should be noted that while high domain averaged IVT is correlated with high precipitation totals (Ralph et al. 2013) the location of the heavy precipitation does not always coincide with the high IVT locations. The heaviest precipitation is often found on the occluded front beneath the cloud head in a region where IVT is low. Finally, Fig. 3c shows the location of cyclone 2 a further 12 h later, at the time of maximum intensity. By this time, the cyclone has traveled to the north of the United Kingdom and the precipitation along the occluded front is becoming less coherent. IVT in the warm sector has also been reduced (Fig. 3e). A third cyclone (labeled “3”) is forming on the trailing cold front of cyclone 2 and is tracking along the same path as cyclone 2 toward the United Kingdom.
In this case, therefore, the high TCWV band shown in Fig. 2d is associated with a family of cyclones all traveling along the same path. This results in multiple precipitation events over the United Kingdom; thus, flooding is exacerbated as the precipitation falls over already wet ground (Hand et al. 2004; Ralph et al. 2004, 2013). Furthermore, a secondary cyclone that follows in the footprints of a previous parent cyclone may profit from the high TCWV band created by the parent, leading to more intense precipitation in subsequent cyclones.

Water vapor budget. In this section, we now examine the individual terms in the water vapor budget equation in order to determine the sources of water vapor contributing to precipitation and transport of water vapor.

Figure 4a shows the surface precipitation flux at 0600 UTC 1 February 2002. This is the same figure as Fig. 2c but shown on a different scale with different units. (It is assumed that precipitation is at the same rate for the entire 6-h period.) Figure 4b shows the surface evaporation flux at the same time. There is widespread evaporation from the sea surface within the domain, although the evaporation fluxes are generally small (<0.2 × 10⁻³ kg m⁻² s⁻¹). The greatest surface evaporation at this time occurs in the cold sector immediately behind the cold front. Figure 4c shows the negative of the rate of change of water vapor in each column of the domain. As the instantaneous specific humidity is only available every 6 h from ERA-Interim, the rate of change of water vapor in each column is calculated using the instantaneous values 6 h prior to and 6 h after the time of interest. This results in a
Fig. 4. Cyclone-centered water vapor budget terms at 0600 UTC 1 Feb 2002: (a) precipitation [term 1 in Eq. (1): P], (b) evaporation [term 2 in Eq. (1): E], (c) vertically integrated rate of change of water vapor [term 3 in Eq. (1): − dq/ dt], (d) vertically integrated total moisture flux convergence [term 1 in Eq. (2): MFCTOTAL], (e) vertically integrated mass convergence [term 2 in Eq. (2): MFCCONV], and (f) vertically integrated advection [term 3 in Eq. (2): MFCADV]. All figures have units of ×10⁻³ kg m⁻² s⁻¹ and are overlaid with frontal positions.

smoother field than would be calculated if fields at higher frequency were available. The dominant feature in Fig. 4c is the dipole of positive and negative values on either side of the cold front. This indicates that water vapor content decreases in columns behind the cold front but increases in columns ahead of the cold front in the warm sector.

The moisture flux convergence term can be calculated as a residual time-averaged value [using Eq. (1)] or as an instantaneous value using the instantaneous specific humidity and wind fields. Figure 4d shows the instantaneous moisture flux convergence, calculated using the system-relative wind fields (calculated by subtracting the system propagation speed from the absolute wind fields). Divergence of moisture occurs behind the cold front and convergence of moisture occurs along the frontal boundaries. The instantaneous moisture flux convergence is similar to that calculated using the time-averaged fields but the magnitude of the fluxes is larger. Averaging the instantaneous moisture flux convergence over three time steps (6 h prior to time of interest, time of interest, and 6 h after time of interest) shows that the difference in the magnitudes is due to the partial cancellation of positive and negative fluxes ahead of and behind the cold front as the cold front moves cyclonically (not shown).

We can split the total instantaneous moisture flux convergence into its convergent and advection components. Figure 4e shows the mass convergence term in Eq. (2) calculated using the analyzed fields. As expected, this field bears a close resemblance to the precipitation field in Fig. 4a, despite being an instantaneous field. Divergence of moisture ahead of the cold front leads to slantwise ascent, condensation of water vapor, and thus precipitation formation. Figure 4f shows the advection term in Eq. (2) calculated using the analyzed fields. Negative
advection of water vapor occurs behind the cold front as the system-relative winds advect relatively dry air behind the cold front cyclonically. Positive advection of water vapor occurs ahead of the cold front as the cold front sweeps high water vapor content into this region. The magnitude and extent of the negative water vapor advection region exceeds that of the positive water vapor advection region. This imbalance results in moisture accumulating along the cold frontal boundary. Thus, the relative motion of the cold front acts to form and maintain the filament of high TCWV values parallel to the cold front as the cyclone moves poleward. Thus, the separation of the total MFC into its convergent and advection components highlights the difference between the formation of the atmospheric river by advection of moisture and the large-scale mass convergence and ascent beneath the cloud head and along the occluded front. The total MFC or IVT cannot distinguish these two processes, which act in different parts of the cyclone.

To further illustrate this point, Fig. 5 shows the moisture flux calculated using the absolute winds and system-relative winds. Although the absolute flow suggests a strong flux of water vapor from outside the cyclone domain toward the cyclone center (Fig. 5a), the system-relative flux of water vapor (Fig. 5b) shows that this is not the case. As the cyclone travels with a speed and direction that is comparable to the wind speed and direction ahead of the cold front, the alongfront component of the system-relative IVT in this region is small and hence the water vapor flux toward the cyclone center is also small. Closer to the cyclone's warm front, the system-relative winds gain an alongfront component before splitting into a cyclonic and anticyclonic branch as the airflow rises up over the warm front (this is identified as the warm conveyor belt airflow; Harrold 1973). Thus, in this region the warm conveyor belt airflow transports water vapor cyclonically into the cloud head and anticyclonically into the cloud shield. The reduced alongfront transport in this Lagrangian framework does not mean that there is no poleward transport of water vapor by the cyclone but that there is little poleward transport of water vapor into the cyclone system itself. Thus, instead of poleward transport occurring because of a direct and continuous feed of moist air from the subtropics to the extratropics (as suggested by the term “atmospheric river”), poleward transport is the result of a continuous cycling of moisture within the cyclone itself. Local convergence of moisture, occurring ahead of the cold front, provides a source of moisture at the base of the warm conveyor belt airflow, which ascends in a slantwise motion, reaches saturation, and forms precipitation. Subsequent convergence of

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**Fig. 5.** Cyclone-centered water vapor transport at 0600 UTC 1 Feb 2002. Surface–500-hPa TCWV (kg m⁻²), as in Fig. 2d, is overlaid with (a) surface–500-hPa moisture flux vectors and (b) surface–500-hPa system-relative moisture flux vectors. Both panels are overlaid with frontal positions. The black arrow head shows the direction of cyclone propagation.
moisture results in a continuous cycle; thus, the saturated air is formed by the cyclone and moves with the cyclone, leaving behind a footprint of where the cyclone has been as the cyclone travels poleward.

**Domain-integrated water vapor budgets.** Figure 6 shows how the domain-integrated terms in the water vapor budget evolve with time for the cyclone on 1 February 2002. The largest term is the domain-integrated precipitation. The precipitation flux increases during the first 24 h of the cyclone lifetime and peaks 12 h before the time of maximum intensity. After this, the domain-integrated precipitation gradually decreases with time. The next largest term is the domain-integrated evaporation flux. Although the evaporation flux is relatively small at each location, the domain-integrated value contributes significantly to the total water vapor in the atmosphere. The domain-integrated rate of change of water vapor is negative \(-\frac{dq}{dt}>0\) throughout the cyclone’s life cycle, indicating that the water vapor leaving the cyclone domain, via precipitation and divergence, exceeds the water vapor entering the cyclone domain via evaporation and convergence. The domain-integrated system-relative moisture flux convergence is relatively small. For this cyclone, it is small or negative during the cyclone’s evolution. As only a small amount of water vapor converges into the domain at the start of the cyclone’s evolution, this implies that local sources of water vapor from within the domain dominate the contribution of water vapor available for cyclone precipitation.

Also shown in Fig. 6 are the terms that contribute to water vapor convergence. As expected, the domain-integrated mass convergence term is positive throughout the majority of the cyclone’s evolution. The domain-integrated advection term is negative and largely balances the local mass convergence term. For this cyclone, therefore, external sources of water vapor (>1500 km from cyclone center) contribute a negligible or even negative amount of water vapor available for precipitation formation. The dominant source of water vapor therefore comes from within the domain.

**CLIMATOLOGY OF 200 NORTH ATLANTIC CYCLONES.** Climatology: Domain-integrated water vapor budgets. Figure 7 shows the domain-integrated water vapor budget for a climatology of 200 extratropical cyclones. The individual terms in the budget are smoother than for the individual case study, but their relative importance does not change. As for the case study, domain-integrated precipitation dominates, peaking 12 h before maximum intensity. This is consistent with the results of Bengtsson et al. (2009). Evaporation also peaks 12 h before maximum intensity. The domain-integrated rate of change of water vapor is negative \(-\frac{dq}{dt}>0\) throughout almost the entire period of the cyclone’s life cycle. The resultant moisture flux convergence is again small and slightly positive in the very early stages of development but becoming negative during the period of maximum intensification and decay.

Local horizontal mass convergence is positive throughout the entire cyclone life cycle and is responsible for transporting water vapor into the base of the warm conveyor belt. In a system-relative sense, water vapor is actually exported from the cyclone during the period of maximum intensification (36–0 h prior to maximum intensity) and during its decaying phase. Thus, the cyclone effectively leaves a footprint of high water vapor content air behind it as it travels poleward.

As a fraction of the total precipitation, external moisture flux convergence contributes a negligible or even negative amount to the vapor available for precipitation formation. These results are consistent with the results of Sodemann and Stohl (2013), who showed that during intense precipitation events in Norway <20% of the water vapor originated south of 50°N. Similarly, Knippertz and Wernli (2010), in a 23-year climatology of tropical moisture export, found that the contribution of tropical moisture to precipitation in the extratropical Atlantic was also below 20%.
Cyclones are identified and tracked in the ERA-Interim 1979–2009 reanalysis using 850-hPa relative vorticity. The individual terms in the water vapor budget equation are calculated for each of the 200 cyclones. Evaporation of water vapor from the sea surface, occurring mostly behind the cold front, contributes significantly to the total cyclone water vapor throughout the entire cyclone life cycle. The total cyclone-integrated water vapor decreases throughout its life cycle as the water vapor lost from the atmosphere by precipitation exceeds that gained via evaporation or water vapor convergence.

Water vapor convergence into and out of the system is negligible and even negative during the most rapidly intensifying stage of the cyclone evolution showing that water vapor is actually exported from the system leaving a water vapor footprint behind the cyclone as it travels poleward. To further investigate this, the local mass convergence and advection of water vapor flux terms are calculated. It is shown that, as the cold front moves cyclonically toward the warm front, causing the warm sector to narrow, local convergence of water vapor occurs along the cold front and is thus responsible for creating the band of high TCWV.

**DISCUSSION AND CONCLUSIONS.** In this paper, we investigate the spatial distribution and transport of water vapor within a climatology of extratropical cyclones. The 200 most intense extratropical cyclones are identified and tracked in the ERA-Interim 1979–2009 reanalysis using 850-hPa relative vorticity. The individual terms in the water vapor budget equation are calculated for each of the 200 cyclones. Evaporation of water vapor from the sea surface, occurring mostly behind the cold front, contributes significantly to the total cyclone water vapor throughout the entire cyclone life cycle. The total cyclone-integrated water vapor decreases throughout its life cycle as the water vapor lost from the atmosphere by precipitation exceeds that gained via evaporation or water vapor convergence.

Water vapor convergence into and out of the system is negligible and even negative during the most rapidly intensifying stage of the cyclone evolution showing that water vapor is actually exported from the system leaving a water vapor footprint behind the cyclone as it travels poleward. To further investigate this, the local mass convergence and advection of water vapor flux terms are calculated. It is shown that, as the cold front moves cyclonically toward the warm front, causing the warm sector to narrow, local convergence of water vapor occurs along the cold front and is thus responsible for creating the band of high TCWV.

**Fig. 7.** As in Fig. 6, but for composite of 200 wintertime North Atlantic cyclones.

**Fig. 8.** (a) Schematic showing positions of surface fronts at successive 12-hourly intervals, starting at 0600 UTC 31 Jan 2002. (b) SSM/I (F13)-integrated water vapor on 31 Jan 2002 overlaid with 0600 UTC 31 Jan 2002 frontal positions. (c) SSM/I on 1 Feb 2002 overlaid with 0600 UTC 1 Feb 2002 frontal positions. (d) SSM/I on 2 Feb 2002 overlaid with 0600 UTC 2 Feb 2002 frontal positions.
Figure 8 is a schematic showing the relative positions of surface fronts and regions of high TCWV for the case study cyclone on 1 February 2002. The band of high integrated water vapor narrows as the cold front moves cyclonically toward the warm front, sweeping up water vapor as it travels. The location of the band of high water vapor travels farther from the cyclone center as the cyclone evolves because of the process of frontal fracturing. By the decaying stage of the cyclone evolution the band is >1000 km from the cyclone center. The filaments of high water vapor content seen in the Special Sensor Microwave Imager (SSM/I) satellite imagery represent the footprints left behind as the cyclone channels atmospheric moisture into a narrow band as it travel poleward from its origin in the subtropics.

This paper supports the conclusions reached in idealized and Lagrangian studies that local sources of water vapor are responsible for the formation and maintenance of bands of high TCWV found ahead of the cold front in the cyclone’s warm sector. Furthermore, it suggests that the filamentary structures of high TCWV are the result of water vapor export, resulting in footprints left behind as cyclones travel poleward.

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LatMix combines shipboard, autonomous, and airborne field observations with modeling to improve understanding of ocean stirring across multiple scales.

Dispersion of natural and anthropogenic tracers in the ocean is traditionally conceptualized as a two-stage process: The first step, stirring, is an adiabatic rearrangement of water parcels that does not change their potential temperature, salinity, or other tracer concentrations; it tends to stretch tracer patches into convoluted streaks and therefore enhances overall variance of tracer gradients. Molecular diffusion then acts to reduce small-scale gradients and effects the ultimate mixing (Eckart 1948; Garrett 2006). In practice, all small-scale processes not resolved in a particular numerical or...
analytic framework (e.g., Reynolds-averaged Navier-Stokes equations) are often lumped into mixing with the understanding that it may include unresolved stirring as well. Within the strongly stratified ocean interior, a clear distinction can be made between isopycnal processes, which act along surfaces of constant potential density (or, more strictly, neutral surfaces; Montgomery 1940; McDougall 1984), and diapycnal processes, which act across these surfaces (Gregg 1987; MacKinnon et al. 2013). Interpretation of lateral dispersion of tracers in the ocean in terms of mixing is fraught with ambiguity. The unresolved flux $J_T$ of a tracer $T$ ascribed to lateral mixing is commonly parameterized with Fickian diffusion law,

$$J_T = -K_h \nabla T,$$

where $K_h$ is the effective diffusivity and $\nabla T$ is the resolved tracer gradient. However, it has been long recognized that $K_h$ depends strongly on the spatial and temporal scales being considered (Stommel 1949; Ozmidov 1958). Therefore, any estimate of $K_h$ must be accompanied with the specification of scales, which are themselves somewhat arbitrarily defined (Okubo 1976). These ambiguities can be overcome by understanding and modeling the processes responsible for lateral stirring of tracers.

Stirring cascades variance from large scales, where it is produced, to $O(1)$ cm scales, where it is removed by molecular diffusion (Stern 1975). On the mesoscale $O(10–100)$ km, isopycnal stirring by geostrophic eddies is well understood (e.g., Smith and Ferrari 2009). Likewise, stirring by microscale ($0.01–1$ m) isotropic turbulence to the molecular scale has been studied for many decades and its physics is well established. In contrast, the dynamics that control stirring on the submesoscale ($0.1–10$ km), and the relative importance of various processes is not as well known. Contributions from both geostrophically balanced motions and internal gravity waves are expected, but their relative importance and the mechanisms by which they stir have not been quantified. Here, we discuss a recent campaign to improve our understanding of submesoscale stirring and mixing in the ocean interior.

Traditionally, dynamic signals at the submesoscale have been thought to be dominated by the ubiquitous presence of energetic broadband internal gravity waves (IGW). Decades of observations of these motions have clearly established their role in controlling diapycnal mixing (Gregg 1989; Polzin et al. 1995; MacKinnon et al. 2013). Although these motions have traditionally been modeled and conceptualized as a superposition of nearly linear IGW, significant deviations from this paradigm have been persistently observed, promoting speculations about the presence of coexisting vortical modes dominated by isopycnal velocities (Lien and Müller 1992; Sundermeyer et al. 2005; Pinkel 2014). IGW have long been thought to also have an important role in isopycnal mixing through shear dispersion, in which vertical internal-wave shear couples with diapycnal mixing (Young et al. 1982, hereafter YRG82). Traditional YRG82 scaling for the resulting effective isopycnal diffusivity is $K_h \sim \langle K \rangle (\partial V / \partial z)^2 f^{-2}$, where $\langle K \rangle$ is the average diapycnal diffusivity and $\langle (\partial V / \partial z)^2 \rangle$ is the average variance of vertical shear dominated by fine-scale near-inertial waves. Dye-release studies have consistently found isopycnal diffusivities $O(1)$ m$^2$ s$^{-1}$ at 1–5-km scales, an order of magnitude larger than could be inferred from YRG82 theory (Ledwell et al. 1998; Sundermeyer and Ledwell 2001). This discrepancy may be due to 1) covariance between internal-wave strain and shear-driven turbulence (Kunze and Sundermeyer 2014, manuscript submitted to *J. Phys. Oceanogr.*), 2) internal-wave Stokes drifts (Bühler et al. 2013), 3) subinertial vortical modes generated by breaking internal waves (Brunner-Suzuki et al. 2014), or 4) submesoscale processes unrelated to internal waves (Mahadevan and Tandon 2006; Capet et al. 2008; Thomas et al. 2008; Molemaker et al. 2010).

Recent high-resolution numerical models and targeted observations reveal intricate patterns of three-dimensional submesoscale fronts and filaments emerging from mesoscale features (Capet et al. 2008). A number of dynamical processes have been proposed to explain this mesoscale–submesoscale transition, including spontaneous instability of deep mixed layers, ageostrophic instability, frontogenesis, and direct wind forcing at mesoscale fronts (Boccaletti et al. 2007; Thomas et al. 2008). Numerical simulations suggest that non-quasigeostrophic baroclinic mixed layer instabilities can penetrate into the thermocline, leading to lateral stirring of tracers below the mixed layer (Badin et al. 2011).

It appears that both internal-wave and subinertial submesoscale dynamics cascade tracer variance and turbulent kinetic energy from larger scales, where they are generated, to dissipate at small scales, but the relative importance of various pathways has not been resolved (McWilliams et al. 2001; Müller et al. 2005; Molemaker et al. 2010). Moreover, it is presently unclear which processes participating in the cascade control downscale flux of variance (Garrett 2006).

The “Scalable Lateral Mixing and Coherent Turbulence” (LatMix) initiative led by the Office of Naval Research tackled the problem of submesoscale oceanic stirring spanning mesoscale to microscale processes from observational, theoretical, and numerical perspectives. Here, we present an overview
of the major 2011 LatMix campaign involving three regional-class research vessels with numerous shipboard, towed, and autonomous instrument platforms, as well as airborne and satellite remote sensing and supporting numerical simulations.

FIELD EXPERIMENT. Aims. The LatMix initiative set out to address the following primary hypotheses for what drives isopycnal stirring and mixing at the submesoscale (while recognizing that the answer may be all or none of these processes):

1) internal-wave shear dispersion in which diapycnal mixing interacts with the vertical shear of the waves;
2) stirring associated with finescale potential vorticity anomalies (vortical modes) caused by internal-wave breaking;
3) progressive straining of tracer fields to smaller scales by mesoscale processes adequately described by quasigeostrophic dynamics; and
4) high-Rossby-number subinertial motions on the submesoscale that are not quasigeostrophic, such as frontogenesis and mixed layer instabilities.

Experimental testing of these hypotheses required observations of submesoscale lateral tracer dispersion at various levels of background mesoscale straining and atmospheric forcing. The LatMix initiative included two major field campaigns, along with several modeling studies, to address processes ranging in scale from $0.01\text{ to }100\text{ km}$. Here, we describe the first field experiment of summer 2011, conducted in the Sargasso Sea in a region of low to moderate straining and shallow mixed layers. The second campaign in late winter and spring 2012 (to be described in forthcoming articles) was situated in the Gulf Stream, a strongly straining flow with strong surface fluxes and deep mixed layers.

Logistics and participants. Three regional class vessels participated in the field campaign: research vessels (R/Vs) Cape Hatteras, Endeavor, and Oceanus. Each vessel carried a wide range of shipboard, towed, and autonomous deployable instrumentation (see Table 1 and appendix). Additionally, R/V Cape Hatteras conducted a series of fluorescein and rhodamine dye releases that were surveyed with all three vessels. Dye patches were also surveyed by airborne lidar on board a Navy Lockheed P3 Orion aircraft. Broad context was established by analysis of satellite remote sensing products and operational numerical models.

Timely collective decision-making and coordination among the science parties on three research vessels required near-real-time integration and sharing of information. Shore support provided automated downloading, subsetting, and packaging of satellite and operational model sea surface height and temperature datasets. These were consolidated with telemetered instrument data streams in a common shoreside database, which was routinely replicated on the research vessels for local use. Positions of the vessels and all the autonomous platforms were plotted in near-real time on situation-awareness displays on the ships’ bridges to aid navigation and avoid collisions. Technical details about the instrumentation and data products used in this study are given in the appendix.

Oceanographic and meteorological context. The summer LatMix experiment was conducted from 1 to 20 June 2011 in the Sargasso Sea approximately 250 km south-southeast of Cape Hatteras and southeast of the Gulf Stream. The area was selected based on water clarity and relative proximity to shore, to optimize conditions for optical remote sensing by the aircraft and for the relative weakness of the mesoscale eddy field required for low- and moderate-dispersion studies. Bathymetry is generally flat and featureless, with the typical water depth of 4–5 km. Upper-500-m ocean stratification was characteristic of the summertime interior subtropical gyre (Fig. 1). Strong surface heating resulted in a shallow (10–20 m) and warm (25°–28°C) mixed layer. The buoyancy frequency below the mixed layer (20–30 m) was on the order of 0.02 s$^{-1}$.

Fair summertime weather prevailed during the experiment (Fig. 2). Average air temperatures of 24.3°C were about 1°C cooler than the sea surface. Winds were typically light (<10 m s$^{-1}$). Two short storms on 12 and 18 June brought precipitation of 50 and 150 mm, respectively; maximum wind speeds of 15 m s$^{-1}$; and short-term cooling.

EXPERIMENT PROGRESS AND MAIN FINDINGS. The summer 2011 LatMix field experiment consisted of weak-straining [0(0.05$f$); 2–10 June] and moderate-straining [0(0.1$f$); 11–19 June] case studies, where $f = 7.7 \times 10^{-5}$ rad s$^{-1}$ is the

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1 Characteristic magnitudes of mesoscale [0(10) km] strain rate tensors in each case study were determined from the maps of mean near-surface (0–50 m) velocity, objectively interpolated from shipboard ADCP observations during the reconnaissance surveys.
Coriolis frequency at 32°N. Sites for the studies were selected based on satellite imagery and coordinated reconnaissance surveys. Geographically, the sites of weak- and moderate-straining studies overlapped; increased straining during the second case study was due to eastward expansion of several warm-core mesoscale eddies.

Each case study started with a coordinated 100 km × 100 km mesoscale survey carried out by the three vessels, followed by ~100-kg rhodamine dye releases on an isopycnal surface in the seasonal pycnocline at depths around 30 m (see appendix for dye injection details). A Lagrangian float was deployed within the dye patch and tracked acoustically. Drogued drifters and profiling Electromagnetic Autonomous Profiling Explorer (EM-APEX) floats were deployed in an array surrounding the patch. Subsequently, the vessels commenced nested surveys of the area centered on the dye: a 30 km × 30 km radiator pattern covered by R/V Oceanus, a 15 km × 15 km butterfly pattern by R/V Endeavor, and an O(1) km adaptive survey by R/V Cape Hatteras (Fig. 3). The surveys were supplemented by a group of four Slocum gliders and one SeaGlider. The surveys were guided in real time by the advection of the Lagrangian float and drogued drifters, as well as by the integral of the R/V Cape Hatteras 150-kHz acoustic Doppler current profiler (ADCP) velocity in the depth bin occupied by the dye. Details about

<table>
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<th>Table 1. LatMix summer field campaign observational and modeling efforts along with the names and affiliations of the principal investigators or chief scientists. Woods Hole Oceanographic Institution (WHOI), School for Marine Science and Technology (SMAST), University of Massachusetts Dartmouth (UMassD), Oregon State University (OSU), Applied Physics Laboratory, University of Washington (APL-UW), NorthWest Research Associates (NWRA), University of Victoria (UVic), Naval Air Systems Command (NAVAIR), Massachusetts Institute of Technology (MIT), New York University (NYU), University of California, Los Angeles (UCLA), and Rosenstiel School of Marine and Atmospheric Science (RSMAS).</th>
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<tr>
<td><strong>R/V Cape Hatteras</strong></td>
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<td>Dye injection</td>
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<td>Acrobat CTD/fluorometer</td>
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<td>OSU Moving Vessel Profiler</td>
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<td>Lagrangian float</td>
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<td>SVP (global) drifters</td>
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<td>Large eddy simulations</td>
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Fig. 1. Profiles of potential temperature (blue), salinity (green), and potential density (red) during LatMix Seaglider deployment (3–10 Jun 2011). Heavy lines indicate the mean profiles. Salinity is reported on the practical salinity scale throughout (nondimensional).

A series of eight smaller (~10–27 kg) fluorescein dye releases were also performed in close proximity in depth and location to the rhodamine experiments. These releases were tracked by towed instruments for about a day each during continued surveys of the rhodamine patches. Four of these fluorescein dye patches were also surveyed for the first 6 h or so of their evolution by airborne lidar. During the daylight hours, after most of the fluorescein deployments, a microprobe-equipped autonomous underwater vehicle Turbulence Remote Environmental Measuring Unit (T-REMUS) was deployed to conduct 1-km box surveys around a drogued Gateway buoy (see appendix) while Hammerhead was towyed in 2-km-radius circles around it. Nested within surveys by Triaxus and Moving Vessel Profiler (MVP) instrument systems, these measurements collectively spanned horizontal scales of 0.03–30 km (Fig. 3).

A Google Earth interactive map of shipboard, autonomous, and airborne surveys during the summer 2011 LatMix experiment is available online as supplemental material (http://dx.doi.org/10.1175/BAMS-D-14-00015.2); see sidebar on supplemental material.

**Weak-straining study.** The weak-straining study started on 2 June 2011 at a quiescent site with lateral velocity gradients of $O(0.05)$ estimated at 10-km scale using the mesoscale map of mean near-surface (0–50 m) ADCP velocities (Fig. 4) and simultaneously inferred from the drifter and dye convergence/elongation at kilometer scale. Lateral thermohaline variability was weak, with the exception of a 0.02 km$^{-1}$ salinity gradient in the mixed layer and a few coherent features with $O(0.1)$ salinity anomalies in the pycnocline (Fig. 5). The upper-ocean flow was dominated by 6–9 cm s$^{-1}$ inertial oscillations, as evident from the looping trajectories of the tracking drifters (Fig. 6). Subinertial advection was initially negligible but increased to 15 cm s$^{-1}$ southward flow by 10 June.

A 1.5-km-long zonal streak of rhodamine dye was released on 4 June 2011 in the upper seasonal pycnocline with the vertical potential density gradient $-0.025$ kg m$^{-2}$ at potential density of 25.42 kg m$^{-3}$ [root-mean-square (rms) deviation of ±0.014 kg m$^{-3}$] and a mean depth of 30 ± 1.4 m (Figs. 5 and 6). The dye release was accompanied by deployment of nine GPS-tracked drifters drogued at 30 m, in a cross pattern, and a Lagrangian float at the center of the streak (Fig. 6). Simultaneously, a swarm of 18 EM-APEX floats forming three concentric circles (1-, 2-, 3- km) were deployed.
face of this confluence implied an isopycnal diffusivity on the order of 1 m² s⁻¹ at the 1–5-km scales of the dye patch.

Tracking the spreading of the array of drogued drifters provided an alternative measure of lateral (but not isopycnal) dispersion. The change in mean-square separation between the nine drogued drifters over the 6-day period gave an upper bound of 0.6 m² s⁻¹ for the effective lateral diffusivity. Moreover, fitting a strain-diffusive model to the second moment of the drifter separation gave a best estimate of lateral diffusivity of 0.2 m² s⁻¹, while the strain rate estimate was in agreement with that mentioned above (3 × 10⁻⁶ s⁻¹ or 0.04 f) (J. Early 2015, manuscript in preparation). This factor of 5 discrepancy in the lateral diffusivity estimates may reflect the differences between dispersion of dye and of drifters: while the dye measures true isopycnal dispersion, the drifters respond to the velocity at the fixed depth of their drogues, which may not have a fixed potential density. Therefore, drifter estimates of dispersion may not always accurately represent the dispersion of tracers.

Short nighttime fluorescein releases were performed on 5, 8, 9, and 10 June. These releases were accompanied by deployment of a second Lagrangian float and three drogued drifters. The fluorescein patches were mapped by R/V Cape Hatteras between or during continued surveys of the rhodamine patch. The fourth fluorescein patch of this set (10 June) was the first one surveyed by airborne lidar.

Moderate-straining study. A saddle point in the flow on the periphery of an O(100) km mesoscale eddy was chosen as the initial location for the moderate-straining case study of 12–20 June 2011 (Fig. 8). A chain of such corotating cyclonic (counterclockwise) eddies appeared to be forming in secondary instability of a larger Gulf Stream meander (Figs. 4 and 8). The saddle point occurred at the edge of a warm, relatively fresh, anticyclonic (clockwise) filament from the eddy intruding into a cooler and saltier northward-flowing filament.
Underneath the surface thermohaline front visible at the stagnation point (Fig. 8) was an upper-pycnocline front of the opposite sense, with saltier, denser, and somewhat cooler water to the west (Fig. 9a, I–IV). High-resolution data from the MVP surveys by R/V Endeavor found salinity differences as high as 0.3 on isopycnal surfaces in the vicinity of this front (Fig. 10). Consistent with the reversal of density gradients below the mixed layer, maximum northward flow exceeding 0.4 m s\(^{-1}\) occurred at middepth (40 m). Kilometer-scale strain rates associated with the front reached 0.5 f.

The early evolution of the upper-pycnocline thermohaline front prior to and immediately after the dye release (12–15 June) is shown in Fig. 10 in isopycnal coordinates. Initially spanning several kilometers, the width of the front sharpened to O(100) m over the course of 4 days.

![Diagram](image_url)

**Fig. 3.** Illustration of the nested sampling from R/V Oceanus (Triaxus, Hammerhead, and T-REMUS), R/V Endeavor (MVP), and R/V Cape Hatteras (Acrobat). Triaxus measured along a 30-km radiator grid (red), MVP made repeated 15-km bowtie surveys (blue), Acrobat performed adaptive surveying of the dye with a 3-km radiator grid, and Hammerhead was towed in 2-km-radius circles (magenta) around 1-km T-REMUS boxes (black) centered on a drogued Gateway buoy (not shown). Gliders surveyed within the 10-km-radius area on multiple intersecting tracks. Subsequent sampling patterns were shifted to keep up with the advection of dye and drifters.

**Fig. 4.** Weak-straining study area prior to the dye release on 4 Jun 2011. (a) AVHRR sea surface temperature image. (b) Sea surface temperature and velocity field objectively interpolated from the observations during the mesoscale reconnaissance survey carried out by all three vessels on 2 and 3 Jun 2011 (ship tracks are shown as gray lines); the map extent is shown with a black square in (a). The red circle marks the site of the drifting array deployment and rhodamine dye release. The red line in (b) shows the drift of the array between 4 and 10 Jun 2011 (see also Fig. 6). The east–west offset in (b) between the array drift track and the flow pattern is likely due to evolution of the flow between the time of the map and the longer period of the drift. Meridional transect along the dashed line is shown in Fig. 5.
as a result of confluence on the order of 0.1f. This sharpening was not monotonic in time because of significant near-inertial vertical shear that tilted isohalines.

Rhodamine was released for the moderate-straining study on 13 June along a 2-km-long line oriented about 20° from true north (Fig. 11). The mean potential density at the release was 25.04 ± 0.011 kg m⁻³ (vertical

**Fig. 5 (left).** Meridional sections of (a) temperature, (b) salinity, (c) potential density, and (d) zonal velocity through the weak-straining study site, based on the Triaxus and shipboard ADCP data from R/V Oceanus on 4 Jun 2011. The magenta rectangle marks the approximate location of rhodamine dye release. The section location is marked with a dashed line in Fig. 4b.

**Fig. 6 (below).** Evolution and advection of the rhodamine dye patch and the arrays of drifters and floats during the weak-straining study (4–10 Jun 2011). (left) The rhodamine patch (magenta), the trajectories of the centers of mass of the drifter array (red) and EM-APEX array (blue), and the interpolated trajectory of the Lagrangian float (green). The sites of rhodamine and fluorescein releases are marked with magenta and cyan triangles, respectively. (right) The configuration of the arrays at the beginning of the study (0700 UTC 4 Jun 2011) and at the end (0000 UTC 10 Jun 2011). The location and extent of each panel is marked on the left with the dashed lines (red for drifters and blue for EM-APEX). North and east distances are relative to the centers of mass of the drifter arrays. A few EM-APEX floats were omitted for clarity. The magenta lines in the 4 Jun panels show the initial rhodamine dye streak.
potential density gradient $\approx -0.04 \text{ kg m}^{-4}$) and mean depth approximately $30 \pm 1.1 \text{ m}$, similar to those in the weak-straining case. Again, the dye patch was marked with nine drogued drifters in an approximate cross pattern and a Lagrangian float. As before, a swarm of 18 EM-APEX floats in three concentric circles (1-, 2-, and 4-km nominal diameters) was also deployed (Fig. 11).

The dye patch and drogued drifters were entrained in the northward branch of the flow, accelerating to $0.4 \text{ m s}^{-1}$ by 14 June. In contrast, northward progress of the EM-APEX floats lagged substantially as a result of strong vertical shear experienced by the floats, since they cycled between the surface and 150-m depth (see appendix). By 16 June, separation between the dye patch and the EM-APEX swarm grew to almost 55 km, straining surveying resources. At the same time, the swarm also stretched into a narrow 20-km-long line, so it could no longer provide adequate spatial coverage for estimates of vorticity. As a consequence, on 17 June, all EM-APEX floats were recovered and redeployed 10 km downstream of the dye patch in a similar but enlarged pattern of concentric circles (2.5-, 5-, and 10-km nominal diameters).

During the moderate-straining case study, a rich structure of submesoscale strands became evident in survey transects, most noticeable in the salinity field (Fig. 9b, II). To what extent these features represented spatial variability in the front versus temporal evolution is not known. Sea surface temperature (SST) imagery (Fig. 12b) suggests fragmentation and warming of the cold filament at the surface. However, the subsurface northward jet advecting the dye and drifters remained coherent and strengthened to $>0.5 \text{ m s}^{-1}$ (Fig. 9b, IV). The dye patch was also unaffected by this fragmentation and remained a coherent continuous streak. By the end of the study, the along-stream extent of the dye patch exceeded 50 km, so daily rhodamine surveys were limited to its north end.

By the end of the second study (17–20 June), the cold filament formed a mushroom-like feature strained by a pair of counterrotating mesoscale eddies (Fig. 12c). The subsurface jet split into several

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**Fig. 7 (right).** Evolution of the normalized mean distribution of rhodamine concentration as a function of height above the dye center of mass during the weak-straining case study shown in Fig. 6. The key gives the time since release. The inset shows the increase of the second moment of dye concentration as a function of time, revealing the weak vertical broadening of the dye patch. The least-squares linear fit (dashed line) corresponds to a diapycnal diffusivity of $5 \times 10^{-6} \text{ m}^2 \text{s}^{-1}$.

**Fig. 8.** Moderate-straining study area prior to the 13 Jun dye release. (a) AVHRR sea surface temperature image; black arrows show a subjective interpretation of the surface flow pattern. (b) Sea surface temperature and velocity field based on the reconnaissance survey carried out by all three vessels between 10 and 12 Jun 2011 (ship tracks are shown as white lines); the map extent is shown in (a). Red dots mark the flow stagnation (hyperbolic) point targeted by the study (see also Fig. 11). Zonal transect along the dashed line is shown in Fig. 9a.
cores and decelerated, while the vertical shear increased (Fig. 9c, IV). The sharp salinity fronts in the upper pycnocline disappeared (Fig. 9c, II). A series of slanted thermohaline interleaving features (intrusions) formed at 40–80 m (Fig. 9c, I–II), possibly a signature of submesoscale frontal instabilities that led to restratification and fragmentation of the front (Shcherbina et al. 2010). The drifters, Lagrangian float, and EM-APEX swarm slowed and dispersed in response to increased vertical shear (Figs. 11, and 12c). The surveyed part of the rhodamine dye patch broadened in the cross-stream direction while its along-stream extent remained in excess of 55 km.

In spite of the stronger background currents characterizing the moderate-strain case, diffusivities inferred from the dye were similar to those for the weak-straining case: namely, a diapycnal diffusivity of less than $10^{-5}$ m$^2$s$^{-1}$ and a 1–5-km isopycnal diffusivity on the order of 1 m$^2$s$^{-1}$ (again assuming a Fickian diffusivity and a steady-state balance between cross-streak confluence and diffusion).

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**Fig. 9.** Zonal sections of temperature (row I), salinity (row II), potential density (row III), and meridional velocity (row IV) during the moderate-straining case study based on Triaxus and shipboard ADCP surveys at approximately (column a) 1900 UTC 13 Jun, (column b) 0500 UTC 17 Jun, and (column c) 1240 UTC 19 Jun. The magenta contour shows the evolution of the rhodamine dye patch. The 13 June section location is marked with a dashed line in Fig. 8b; other sections were similarly positioned in the frame of reference advecting with the drifters. The distances are eastward relative to the center of mass of the drifter array.
During the moderate-straining study, short nighttime fluorescein dye releases were performed along the drift track on 15, 16, and 18 June (one to the east and two to the west of the main rhodamine streak). The first two fluorescein patches were surveyed by R/V Cape Hatteras, the T-REMUS autonomous vehicle, and airborne lidar (airborne surveys of the last fluorescein patch were prevented by a line of energetic thunderstorms that passed over the experimental site for several hours while the aircraft stood by).

**Lidar studies of kilometer-scale dye dispersion.** As with laboratory dye experiments, details of dispersion processes are best studied before different parts of the dye patch overlap with one another. Furthermore, one wants a time series of synoptic views of the dye as it evolves: something very difficult to obtain from a research vessel with towed instruments. Thus, the experimental program included rapid surveys with airborne lidar (see appendix for details). The lidar system used was tuned to the absorption and emission bands of fluorescein. Hence, relatively short-duration fluorescein dye-release experiments were done simultaneously and in close proximity in depth and location to the rhodamine experiments. The lifetime of fluorescein is short in sunlight and the insolation at the study site is strong, so the releases were done at dusk and the flights took place that same night, with the plane on site for up to 6 hours. The fourth fluorescein release during the weak-straining case study and the first two fluorescein releases during the

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**Fig. 10.** (a)–(e) High-resolution zonal MVP sections showing evolution of a north–south-oriented thermohaline (spice) front in the vicinity of the rhodamine dye patch between 13 and 15 Jun 2011 under a ~0.1f confluence. The vertical axis is an isopycnal (semi-Lagrangian) depth: namely, the average depth of an isopycnal, and corresponding potential density values are marked on the right in (a). The magenta contour shows evolution of the rhodamine dye patch. (f) Location of sections shown in (a)–(e) in the advected frame of reference moving with the center of mass of the drifter array (red circle). The arrow shows the mean advection direction during the 13–15 Jun period.
moderate-strain study were successfully surveyed by airborne lidar. An impromptu fluorescein release at the surface on 16 June was surveyed with the airborne lidar, showing the evolution of the dye distribution in the mixed layer over the first couple of hours. All of the fluorescein patches were surveyed with the towed instruments from R/V Cape Hatteras.

The lidar surveys showed multiple instances of sinuous meanders of the patches in the first few hours of their evolution, and evidence of filamentation along their peripheries. Such features suggest the presence of weak small-scale (<1 km) differential lateral advection acting on the patches, possibly contributing to the enhanced dispersion seen at later times in the rhodamine experiments. Multiple fluorescein releases also exhibited banding of the dye (not shown), which may have been the result of internal waves or an instability mechanism, the details of which are under investigation.

In addition to the aforementioned filamentation, the 15 June fluorescein experiment showed finger-like structures stretching westward relative to the main patch (Fig. 13). It is believed that these are an artifact of the injection, which was not perfectly along isopycnals but crossed a train of internal-wave crests and troughs corrugating the isopycnal surfaces with a ~40-m horizontal wavelength. The dye streak was then vertically sheared so that dye on
shallower density surfaces was advected westward relative to deeper layers. That the resulting dye fingers persisted for more than 5 h after injection despite their relatively small scale suggests that the effective lateral diffusivity acting at the scale of these features must have been weak. Cross-finger confluence, which could potentially help maintain their sharpness, appears to be ruled out because of the approximately constant separation between the fingers. An upper bound on effective horizontal diffusivity across the fingers estimated from scaling gives $K_h \lesssim (40 \text{ m})^2/5 \text{ h} = 0.1 \text{ m}^2 \text{ s}^{-1}$; that is, nearly an order of magnitude smaller than the effective diffusivity estimated at 1–5-km scales. However, 5 h may not be long enough for the intermittent diapycnal turbulent mixing events that contribute to shear dispersion to have occurred during this interval. Such spatial and temporal intermittency highlights the difficulties
of describing lateral dispersion in terms of a single effective diffusivity on short time and space scales.

During the 16 June surface mixed layer experiment (not shown), airborne lidar surveys revealed a rich structure of coherent roll vortices, apparently extending to the base of the mixed layer. Within the first 0.25–1.6 h, the patch developed a banded structure oriented in the southwest–northeast direction as it was advected downwind (southwest). The wavelength of the bands was on the order of 100 m. Dye in the bands near the base of the mixed layer appeared to lie upwind of the shallower, more rapidly advected dye. Numerical simulations (Sundermeyer et al. 2014) suggest this banding may have been driven by mixed layer instability associated with a lateral density gradient.

**Near-field (meter scale) shear and dye studies.** The $O(1)$ m scale structure of the dye immediately after injection was measured by a custom-built Lagrangian float (see appendix for details) deployed in the middle of each fluorescein injection, typically 1–10 m from the actual streak. The float took about 1 h to sink to the dye level and was tracked acoustically relative to R/V Cape Hatteras. A temperature sensor and a fluorometer profiled across the 1.2-m height of the float every 30 s (Fig. 14a). The float was programmed to remain on the injection isopycnal as measured by two sensors on the ends of the float. The float thus measured an approximately 1.2-m high swath of dye and temperature centered on the injection isopycnal. A Nortek Vector velocimeter measured three components of velocity relative to the float at a point about 1 m below the float’s center of buoyancy: that is, effectively measuring 1-m vertical shear. The 1000-s rms velocity, averaged over all deployments, was $15 \pm 4$ mm s$^{-1}$, which

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**Fig. 14.** (a) Cartoon of the Lagrangian float used in near-field dye studies. The float actively changed its buoyancy to straddle the target isopycnal as measured by CTDs on its top and bottom. A chain drive (gray) repeatedly carried dye and temperature sensors across the float’s length. A Doppler sonar measured the velocity at a point below the float. (b) Dye (colors) and temperature (contours; heavy contour interval of 0.1°C; temperature at the center of the float is about 24.23°C) near the start of a float record during the 15 Jun dye release. Mapping is from upcasts of each sensor only. A persistent streak (“Ref”) results from a reference mark used to align the sensors. (c) As in (b), but later in the record. The float is drawn to scale relative to the data plots.
is consistent with internal-wave variability on this scale; the motion of the float relative to the dye was significantly less.

Figures 14b and 14c show two representative swaths of dye and isotherms obtained during the 15 June 2011 fluorescein dye experiment. The float first encountered dye about 1 h after injection (Fig. 14b). The distribution of dye was highly irregular, changing from greater than 70 ppb to less than 1 ppb in less than 1000 s, corresponding to a distance of only a few meters at a few millimeters per second relative velocity. Figure 14c, taken about 7 h later on the same deployment, shows a more uniform distribution, with straining of dye and temperature by internal waves, but with nearly as large variations in dye concentrations over a few hours. Such large variations are consistent with visual observations of the dye as it emerged from the injector, which suggested an energetic set of turbulent vortices generated by the injector. Because of this variability, no consistent pattern of dye dilution over the 1-day deployments could be found in the float data.

Separating internal waves from vortices and quantifying turbulent mixing with a swarm of EM-APEX floats.

One of the objectives of the summer 2011 LatMix experiment was to separate internal waves from vortical structures (T. Sanford and R.-C. Lien 2015, manuscript in preparation). To do this, it is necessary to observe potential vorticity which, in linearized form, requires observations of the relative vorticity and vortex stretching on spatial scales of 10 m–10 km, in coordination with multiple complementary observations. The swarm of EM-APEX floats produced more than 9,000 velocity, temperature, and salinity profiles in the three deployments (see appendix for details). Of these, more than 2,000 vertical profiles included measurements of high-frequency temperature fluctuations using dual thermistors. With the high 120-Hz sampling rate of FP07 thermistor and the vertical profiling speed of the float (~0.15 m s⁻¹), the inertial and dissipative subranges of the temperature gradient spectrum were well resolved. The thermal variance dissipation rate $\chi$, turbulence kinetic energy dissipation rate $\varepsilon$, and the vertical diffusivity $K_v$ are computed following the method described in Moum and Nash (2009) (Fig. 15).

Internal waves and turbulence in the upper 150 m were measured by the swarm of EM-APEX floats in both the weak- and moderate-straining case studies, for which the WKB-scaled internal wave energy was ~0.5 and 0.9 times the canonical internal-wave level in the main pycnocline, respectively (Garrett and Munk 1979). The diapycnal diffusivity inferred at the dye level is ~5 × 10⁻⁶ and 10⁻⁵ m² s⁻¹ (Fig. 15c). These values are of the same order, if a bit larger than would be expected given the internal-wave field in the main pycnocline from the parameterization of Gregg (1989) and Polzin et al. (1995), and are in agreement with the diapycnal diffusivity inferred from the rhodamine experiments.

**Fig. 15.** Average diapycnal profiles of (a) thermal variance dissipation rate, (b) turbulent kinetic energy dissipation rate, and (c) diapycnal eddy diffusivity derived from the three deployments of microstructure EM-APEX floats in weak-straining (3–10 Jun: black) and moderate-straining (12–16 Jun: red; 16–19 Jun: blue) case studies. The shading shows 95% confidence intervals. The circles and horizontal bars are values and confidence intervals at the target isopycnals of rhodamine dye releases.
Density and velocity fields measured by the EM-APEX float array allowed direct estimation of the fluctuating part of linear potential vorticity, defined as the sum of relative vorticity \( \zeta = v_x - u_y \) and vortex stretching \( -f \partial_t \eta \). Here, \( \eta = -\rho' (\partial_z \bar{\rho})^{-1} \) is the vertical displacement of isopycnals, calculated from the mean background density profile \( \bar{\rho} \) and instantaneous density deviations \( \rho' = \rho - \bar{\rho} \). Linear potential vorticity variations had rms values of \( \sim 0.1f \) and \( \sim 0.5f \) during the weak- and moderate-straining case studies, respectively, but may include internal-wave advection of background PV gradients. The EM-APEX float measurements promise to provide a means of separating vortical motions from internal-wave motion, as planned.

**Glider observations.** Four gliders were deployed in each case study, performing separate 12-km-long transects relative to the drifting array (Fig. 16d), to characterize the variability of thermohaline properties and turbulent microstructure (see appendix for details). During the moderate-straining experiment, glider observations revealed an abundance of structure in the temperature, salinity, and temperature variance dissipation (\( \chi \)) fields (Figs. 16a–c) along the subsurface thermohaline front at 35–65-m isopycnal depth (\( \sigma_\theta = 25.0–25.5 \text{ kg m}^{-3} \)). A higher level of temperature variance dissipation was associated with the warmer, saltier interleaving features in the vicinity of the front (Fig. 16e). Below this interleaving region, there was a pronounced layer of small-scale low-salinity

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**Fig. 16.** Glider-based observations of (a) salinity, (b) temperature, and (c) dissipation of temperature variance during the moderate-straining case study (13–19 Jun 2011) as functions of time and isopycnal (semi-Lagrangian) depth; corresponding potential density values are marked on the right in (a). (d) All glider trajectories (gray) in the advected frame of reference moving with the center of mass of the drifter array (red circle). Trajectory of the single glider used to make the sections in (a)–(c) is shown in black. The glider turning points are marked with the vertical dashed lines and capital letters A–C; trajectory segments from point A to B (red) and from B to C (blue) are highlighted in (d). (e) Dissipation of temperature variance at \( \sigma_\theta = 25.0 \text{ kg m}^{-3} \) as a function of salinity; isopycnal level is marked with the horizontal dashed line in (a)–(c). Highest dissipation values occur in the warmer, saltier patches.
Examination of the shear-dispersion hypothesis. The two rhodamine experiments provide an opportunity to evaluate the shear-dispersion hypothesis as the main mechanism responsible for the isopycnal diffusivity of 1 m$^2$ s$^{-1}$ inferred from the dye spreading (D. Birch et al. 2015, manuscript in preparation).

In both 6-day rhodamine experiments conducted during LatMix 2011, the dye patches elongated in the alongfront direction and compressed in the cross-front direction, as expected under the confluences. To evaluate the contributions of the vertical shear and lateral strain to the observed changes of the patch geometry, a simple semianalytical advection–diffusion model was used. The evolution of the length, width, and tilts of the dye patches was simulated using velocities measured by shipboard ADCPs, a Lagrangian float, and the nine drifters. Velocity gradients in the model were assumed to be constant across the dye patch but were allowed to vary in time. Diapycnal diffusivities on the order of $5 \times 10^{-4}$ m$^2$ s$^{-1}$ inferred from the spreading of the dye in density space and from EM-APEX observations of dissipation (Fig. 15c) were imposed. Thus, shear dispersion arising from interaction of the resolved vertical shear (due to both internal waves and subinertial flows) and diapycnal mixing was explicitly included in the model. Explicit shear dispersion was not strong enough to account for the observed evolution of the dye patches in the context of this model. Isopycnal diffusivity due to the linearized shear field and diapycnal mixing was on the order of 0.1 m$^2$ s$^{-1}$. However, an isopycnal diffusivity an order of magnitude greater is required to explain the ~1 m$^2$ s$^{-1}$ dispersion rate at scales of 1–5 km seen in the observations.

Unresolved shear is also unlikely to account for the observed isopycnal dispersion: traditional YRG82 internal-wave shear dispersion gives effective isopycnal diffusivity $K_\gamma \sim (K)(\partial\nu/\partial z)^2$ inferred from the observations. This is true whether $(\partial\nu/\partial z)^2$ is based on ADCP observations or bounded by the Richardson number stability criterion of $(\partial\nu/\partial z)^2 \leq 4N^2$, where $N$ is the buoyancy frequency. One possible explanation for the discrepancy is higher-order dynamics hitherto not accounted for in the traditional application of YRG82 shear-dispersion theory. Specifically, the YRG82 theory of internal-wave shear dispersion assumes uncorrelated Gaussian statistics for diapycnal diffusivity and shear. Since turbulence is produced by very intermittent internal-wave breaking, high shear and turbulence are both intermittent and correlated. A more appropriate expression for internal-wave shear dispersion then might be $\langle K(\partial X/\partial z)^2 \rangle$, where $\langle \partial X/\partial z \rangle = \int (\partial V/\partial z) dt$ is the vertical gradient of the horizontal displacement $X$ (Kunze and Sundermeyer 2014, manuscript submitted to J. Phys. Oceanogr.). Taking typical turbulence intermittency of 0.05–0.1, for correlations of 0.5 or higher, effective isopycnal diffusivities of $O(1)$ m$^2$ s$^{-1}$ are obtained, so that internal-wave shear dispersion cannot be ruled out. Proving that the latter dominates over other hypothesized mixing and stirring mechanisms remains an observational challenge.

Process modeling. Submesoscale-resolving simulations with O(100) m horizontal resolution and a two-equation algebraic closure model for subgrid turbulence were performed to examine submesoscale stirring (S. Mukherjee et al. 2015, manuscript in preparation).

The simulation was initialized with a 20-m deep mixed layer front with lateral buoyancy gradient $3 \times 10^{-2}$ s$^{-2}$ over 7 km and a baroclinic front with lateral gradient $1 \times 10^{-2}$ s$^{-2}$ extending to 100 m to mimic the kilometer-scale gradients observed during the moderate-straining study on 13 June (Fig. 9a). Both an unforced spindown run and a run forced with the observed hourly wind stress were performed (see appendix for details).

The spindown simulation showed development of submesoscale subinertial instabilities of the thermohaline front and their evolution into streamers and filaments (Fig. 17). The simulation did not have any horizontal mesoscale confluence or mesoscale strain, which would likely stretch the features in the north–south direction. McWilliams et al. (2009) have theoretically shown that these instabilities persist when strain is imposed.

Lateral stirring associated with the instabilities produced salinity intrusions below the mixed layer, with characteristic scales of O(2–5) km in length and O(10) m in thickness. The simulated intrusions were somewhat larger than those observed during LatMix (Fig. 10) but had a similar aspect ratio. Resulting tracer dispersion corresponded to an effective lateral diffusivity of 1–5 m$^2$ s$^{-1}$ at 1–10-km scale. Simulated isopycnal salinity gradient spectra below the mixed layer were flat (i.e., variance was independent of scale) for both spindown and wind-forced simulations in the resolved range (0.5–10 km), in agreement with the LatMix observations (Kunze et al. 2015).
DISCUSSION AND SUMMARY. The 2011 LatMix field campaign accomplished several objectives on the way to its main goal of testing hypotheses for the mechanisms of lateral dispersion in the seasonal pycnocline at scales of 0.1–10 km. The 6-day duration of the rhodamine experiments ranks among the longest for fluorescent dye studies in the stratified ocean. Estimates of diapycnal and isopycnal diffusivity of the dye at the desired scales promise to be robust. Diapycnal diffusivity of the dye, averaged over several days and over tens of square kilometers of fluid (<\(10^{-5}\) m² s⁻¹), and the diffusivity of heat determined from profiles of temperature variance dissipation rate from the EM-APEX floats over the same time and space scales (\(5 \times 10^{-6}\) to \(10^{-5}\) m² s⁻¹) appear to be consistent with one another. Measurements of dissipation rates of turbulent kinetic energy and temperature variance from the T-REMUS autonomous underwater vehicle deployed for approximately 8-h periods are also consistent with the dye and EM-APEX measurements.

The campaign has shown the practicality of airborne lidar observations of dye patches during the first 6 hours of their evolution. The lidar effort is providing unique high-resolution, nearly synoptic surveys of the dye patches, from which ideas of the kinematics of dye dispersion at scales from 0.1 to 1 km may be formed. An unanticipated benefit of the lidar/dye work is a unique look at the evolution of a dye patch in the mixed layer, which provides evidence of stirring by a relatively recently recognized class of mixed layer instabilities (Sundermeyer et al. 2014).

The towed instruments, especially from the Moving Vessel Profiler on R/V Endeavor and Triaxus and Hammerhead on R/V Oceanus, give intriguing data on temperature–salinity (T/S) variability and its evolution in the vicinity of the weakly and moderately straining fronts on which the fieldwork was focused. For example, using salinity anomalies as a natural passive tracer, Kunze et al. (2015) reported a redder spectrum on the submesoscale than predicted by quasigeostrophic theory (Charney 1971; Scott 2006) as has previously been found (Ferrari and Rudnick 2000; Cole and Rudnick 2012; Callies and Ferrari 2013), implying additional straining submesoscale flows that might include contributions from nonquasigeostrophic subinertial flows and internal-wave processes.

Fig. 17. Numerical submesoscale-resolving simulation of thermohaline front instability. (a) Zonal and (b) isopycnal sections of salinity 6.7 inertial periods after the initialization. The vertical axis in (a) is an isopycnal (semi-Lagrangian) depth; corresponding potential density values are shown on the right. Dashed lines mark the locations of isopycnal (25.52 kg m⁻³) and zonal (10 km) sections. The simulation was initialized with the observed thermohaline gradients (smoothed to 1 km) from the 13 Jun hydrograph (Fig. 9a) and allowed to evolve freely (spin down).

A kinematic model based on the observed lateral strains, vertical shears, and diapycnal diffusivities suggests that traditional shear dispersion based on either resolved subinertial or unresolved internal-wave shears cannot account for the \(O(1) m^2 s^{-1}\) isopycnal dispersion exhibited by the dye patches at scales of 1–5 km. However, accounting for intermittency and log normality of turbulence and possible correlation between \(K_v\) and shear (\(\partial V/\partial z\)) suggests a possible way to restore the role of shear dispersion.

Numerical simulations have been performed in concert with the 2011 LatMix experiments by several groups in order to examine and test mechanisms of dispersion. Quasigeostrophic simulations have been run to isolate the role of stirring by mesoscale eddies in the LatMix region from additional stirring due to internal waves and submesoscale mixed layer instabilities. Submesoscale-resolving models have demonstrated stirring and mixing by frontal (S. Mukherjee et al. 2015, manuscript in preparation) and Kelvin–Helmholtz (Skyllingstad and Samelson 2012) instabilities. Large eddy simulations have reproduced the behavior of the mixed layer dye patch, pointing to the instability mechanism responsible for its behavior (Sundermeyer et al. 2014). Large eddy simulations have also been used to examine the behavior of a dye patch in an internal-wave field constructed to simulate that of the LatMix 2011 site with results that promise to sort out the effects of shear dispersion, adiabatic dispersion by internal waves alone, and vortical motions induced by diapycnal mixing events (M.-P. Lelong et al. 2015, manuscript in preparation).
Among the original LatMix hypotheses, we considered four classes of motions that might dominate submesoscale stirring in the seasonal pycnocline: shear dispersion by internal waves; vortices induced by diapycnal mixing events; a downward cascade of stirring motions from the mesoscale; and submesoscale instabilities. We are not yet in a position to rule out any of them, and in fact a reasonable hypothesis at the moment seems to be that they all contribute. In the 2011 LatMix campaign, however, we have gathered data that are enabling us to better describe and quantify each class of motion. Already, in the analysis and synthesis of the observations and the models, new ideas as well as new questions have arisen. The program has brought together investigators with many perspectives, insuring that synthesis will continue to be lively and critically thorough.

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In memoriam of Murray Levine.

**APPENDIX: INSTRUMENT/PLATFORM DESCRIPTION.** *Shipboard instruments.* ADCP: Each of the three research vessels was equipped with a pair of Teledyne RD Instruments acoustic Doppler current profilers (ADCPs): 150- and 600-kHz Workhorse ADCPs on R/V *Cape Hatteras* and 300-kHz Workhorse and 75-kHz Ocean Surveyor on R/Vs *Endeavor* and *Oceanus*. Vertical resolution varied from 2 to 8 m. All ADCP data were collected and processed using the University of Hawaii Data Acquisition System (UHDAS) data acquisition, processing, distribution, and monitoring system (Firing and Hummon 2010).

UCTD: Each vessel was also equipped with an underway thermosalinograph (UCTD) to continuously monitor near-surface temperature and salinity from a flow-through system.

**Towed instruments.** Dye injection: The density of the rhodamine water tracing (WT) and fluorescein dye mixtures was adjusted to within 1 kg m⁻³ of the density of the target seawater by diluting with isopropyl alcohol in 200-L drums. The dye mixture was injected by pumping from the drums through a garden hose coupled to the CTD cable with cable ties. At the end of the CTD cable hung a depressor weight about 1 m below the termination, and streaming about 2 m behind the termination was a neutrally buoyant package comprising a frame, flotation, a Seabird-9 CTD, and a T-shaped diffuser at the end of the garden hose. The package was kept within less than 1 m rms of the target density surface by manually controlling the CTD winch in response to the density deviation measured by the CTD. The system was towed from the waist of the ship, to minimize the effect of ship motion, at a speed of about 1 knot (kt; 1 kt = 0.51 m s⁻¹) for approximately 1 h for the rhodamine releases and 15 min for the fluorescein releases. The ship’s heading was determined by the wind and sea state to minimize ship motion and keep the wire away from the hull. Towing while injecting had the disadvantage of creating turbulent wake, which spread the dye in density space. However, the turbulence also had the positive effect of diminishing the density anomaly of the dye mixture by dilution. Releasing the dye in a streak rather than a spot also had the advantages of making the dye easier to sample early in the experiments and of allowing the dye to sample a variety of mixing conditions from the very beginning.

Triaxus is a towed, undulating vehicle designed for making quasi-synoptic, high-resolution, three-dimensional surveys of the upper ocean. During the LatMix 2011 experiment, Triaxus was typically towed at 7–8 kt while undulating between the surface and 100 m, producing along-track horizontal resolution of about 1 km. The sensor suite included a Seabird CTD, upward- and downward-looking ADCPs, dye fluorometer, transmissometer, and dissolved oxygen sensor, with a fiber-optic tow cable providing telemetry.

Moving Vessel Profiler (MVP), manufactured by ODIM Brooke Ocean/Rolls-Royce, employs an instrumented free-fall fish to measure vertical
profiles of pressure, temperature, conductivity, and rhodamine dye fluorescence down to 50–200-m depth while underway at 6–8 kt. During the LatMix 2011 experiment, typical horizontal spacing of 100-m depth profiles was 0.55 km at 7 kt. Two MVPs were used during the LatMix 2011 experiment: UVic MVP on R/V Endeavor and the OSU MVP on R/V Cape Hatteras.

The Acrobat (manufactured by Sea Sciences, Inc.) is a winged towed body that uses its control surfaces to modulate its depth. For the LatMix program, it was equipped with an RBR CTD and three Turner Cyclcops fluorometers, one each to sense rhodamine, fluorescein, and chlorophyll-a. The majority of the rhodamine dye surveys and three of the six fluorescein dye surveys conducted during LatMix 2011 were conducted with the Acrobat. Vertical resolutions of the surveys were typically on the order of 10 cm within the dye patches, whereas horizontal resolutions were on the order of 150 m.

Hammerhead is a Rockland Scientific towyo body equipped with pumped Seabird temperature and conductivity sensors; a pressure sensor; an electromagnetic (EM) velocity sensor to measure motion through the water; and Chelsea fluorescein, rhodamine, and chlorophyll optical sensors. LatMix 2011 was its first open-ocean use and it was deployed eight times. It conducted 2-km-radius circles around the Gateway buoy for 5–9-h intervals, while T-REMUS was conducting 1-km box surveys. It was towyoed in a 10-m vertical aperture about the target density of the rhodamine and fluorescein dye injections.

**Autonomous platforms.** Four Slocum Electric gliders (Teledyne Webb Research) were deployed to fly a coherent survey pattern relative to the moving drifter that marked the approximate location of the rhodamine dye patch. The coherent survey pattern for the gliders was a 12-km-long tic-tac-toe with two gliders running parallel lines separated by 4 km (e.g., north to south) and the other two gliders running perpendicular lines (e.g., east to west). Two gliders (350-m Webb Slocum) were equipped with 1-Hz CTD (SBE 41); single-wavelength backscatter, chlorophyll, and rhodamine fluorescence (WETLabs FLBBRH); fluorescein fluorescence (FLUR); and 600-kHz phased array DVL (RDI); gliders John (unit 185) and June (unit 186). Two gliders (200-m Webb Slocum) were equipped with CTD (SBE 41) and homemade microstructure packages with two thermistors, two shear probes, and a six-port pressure sensor “gust probe”: gliders Doug (unit 93) and Russ (unit 91). The gliders undulated from about 2-m to 200- or 350-m depth at a vertical rate of 15 cm s⁻¹. The horizontal speed of the gliders was 25 cm s⁻¹. Vertical resolution was less than 1 m and along-track resolution was less than 1 km. The 600-kHz ADCPs on John and June were set to 4-m vertical bins and 10-s ensembles sampling at about 1 Hz. Absolute velocity profiles were computed from all the velocity measurements between glider surfacings (Ordonez et al. 2012).

Seaglider: A fifth glider (1000-m UW Seaglider) was equipped with 0.5-Hz CTD (SBE 41), dissolved oxygen (SBE 43), single wavelength backscatter, chlorophyll and colored dissolved organic matter fluorescence (WETLabs FLNTU), and photosynthetic active radiation (Satlantic) sensor: glider sg158. The Seaglider undulated from the surface to 1000-m depth at a vertical rate of about 20 cm s⁻¹. The CTD was sampled at 4–120-s intervals depending on depth range (higher resolution near the surface). A full dive took approximately 6 h. Horizontal speed was 20 cm s⁻¹, leading to a horizontal resolution of about 5 km.

T-REMUS is a custom-designed REMUS 100 autonomous underwater vehicle (AUV) manufactured by Hydroid Inc. It is 2-m long, 19-cm diameter, and 63 kg in mass. It has a depth range of 100 m and can be deployed for up to 20 h. During the LatMix 2011 experiment, T-REMUS was operated on seven separate runs typically on the order of 8 h in a yoyo mode spanning the depth range of 25 to 45 m using a 10° descent/ascent angle. A Lagrangian three-buoy drogued system (Gateway buoy) was developed to provide navigation and communication with T-REMUS. This configuration allowed the AUV-based measurements to be both along and across prescribed isopycnals and to be taken in an approximate Lagrangian coordinate system with respect to the mean flow at the center depth of the drogue. Sensors on the T-REMUS include the Rockland Scientific MicroRider microstructure measurement system, upward- and downward-looking 1.2-MHz RDI ADCPs, a Seabird SBE 49 "FastCAT" CTD, and a WetLabs ECO Puck Triplet, combining a spectral backscattering meter and a chlorophyll fluorometer.

**Drifters and floats.** The EM-APEX is a Teledyne Webb Research Inc. APEX float with dual, orthogonal electrode arms, which sense the motionally induced electric currents in the ocean (Sanford et al. 2005). In addition to measuring the velocity profile derived from the electric field measurements, relative to a depth-uniform offset, the float measured temperature, salinity, and pressure with a SeaBird 41 CTD. A total of 21 floats were available, and 10 floats also carried a pair of FP-07 fast-response
thermistors and a SeaBird 41CP CTD to observe \( \chi \), a measure of thermal variance dissipation rate. The floats were programmed to profile continuously and synchronously from the surface to 150 m, a cycle that required about 50 min. Profiles of pressure, temperature, salinity, velocity, and surface GPS positions were transferred via iridium before the swarm began the next synchronized dive. Depth-uniform velocity offsets were corrected by considering the integral drift of the floats over the duration of each dive estimated from surface GPS fixes. Uncertainty of the resulting absolute velocities was 1–2 cm s\(^{-1}\) based on the RMS velocity differences of nearby simultaneous profiles. Three swarm deployments were made, with a few floats also recovered and redeployed for repair or to improve spatial coverage. The float data were received and archived at APL-UW and retransmitted to R/V Endeavor via HiSeasNet. The raw microthermistor measurements were retrieved only on instrument recovery after each deployment.

The drogue drifters released with the dye by the University of Massachusetts Dartmouth team consisted of a 40-cm-diameter surface float with a polyvinyl chloride (PVC) spar holding a strobe and a satellite-tracked ComTech GPS device. The surface float was tethered via a 3-mm-diameter Maxibraid tether to a 6.3-m-long, 1-m-diameter holey sock drogue, typically centered at the target dye injection depth. For drogue depths and tether lengths used in the present study, a drag ratio of ~40:1 was maintained between the drogue and tether plus surface expression of the drifter. Drifters were tracked in real time, with position fixes at 0.5-h intervals relayed to the ship and an estimated horizontal accuracy ranging from 10 to 100 m.

SVP drifters: 20 standard Surface Velocity Program (SVP) drifters were deployed during LatMix 2011 in collaboration with the Global Drifter Program administered by the National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory. Each SVP drifter consisted of a satellite-tracked surface buoy and a subsurface drogue centered at a depth of 15 m. Drifter sensors measured sea surface temperature, which was averaged over a 90-s window and telemetered to shore via Argos satellite network. Positions of SVP drifters were determined from Argos signal Doppler shifts, with an estimated accuracy of 250–1500 m. Relatively high positional uncertainty make SVP drifters of limited use for dispersion studies (Haza et al. 2014).

Lagrangian floats (D’Asaro 2003) are meter-sized subsurface neutrally buoyant autonomous instruments, designed to accurately follow the three-dimensional motion of water parcels through a combination of neutral buoyancy and high drag provided by a folding horizontal drogue. For the LatMix experiment, one of the floats was outfitted with a rotating chain-drive mechanism, transporting a SeaBird SBE-39 temperature sensor and a Wetlabs ECO-FLURB fluorometer across the 1.2-m height of the float every 30 s (Fig. 14a).

**Remote sensing and models.** The lidar system, tuned for fluorescein, was flown in a Navy P3 Orion aircraft. Complete surveys of the patch took an hour or so, and the aircraft was over the site for as many as 6 h so that multiple surveys could be acquired. Nominal resolution of the surveys was approximately 10 m in the horizontal by 1 m in the vertical; the surface swath of the conically swept lidar beam was about 200 m.

High-resolution SST imagery was obtained from Advanced Very High Resolution Radiometers (AVHRR) on board NOAA-15, NOAA-18, NOAA-19, and *Meteorological Operational-2* (MetOp-2) satellites. Gridded L3 data were obtained from NOAA CoastWatch data center (http://coastwatch.noaa.gov/). Additional high-resolution SST data, plus maps of diffuse attenuation coefficient (K490; proxy for water clarity) were obtained by the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometers (MODIS) on board the *Aqua* and *Terra* satellites and processed by the NASA Jet Propulsion Laboratory Ocean Biology Processing Group and the University of Miami, Miami, Florida. Lower-resolution SST maps from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) were obtained from Remote Sensing Systems. Near-real-time access of MODIS, TMI, and AMSR-E data were facilitated by the Group for High Resolution SST Master Metadata Repository.

Satellite altimetry products, including along-track and merged absolute dynamic topography maps, were produced by Segment Sol Multimissions d’Altimétrie, d’Orbitographie et de Localisation Précise (SSALTO)/Developing Use of Altimetry for Climate Studies (DUACS) and distributed in near–real time by Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO), with support from the Centre Nationale d’Etudes Spatiales, France (www.aviso.oceanobs.com/duacs/).

Operational models: Regional-scale predictions from the Hybrid Coordinate Model and the Global Navy Coastal Ocean Model were produced by the Naval Oceanographic Office using the Navy Coupled
Ocean Data Assimilation system and obtained via distribution by the Hybrid Coordinate Ocean Model (HYCOM) Consortium and by the Naval Oceanographic Office (NAVOCEANO), respectively.

Process model: The Process Study Ocean Model (PSOM) is a three-dimensional, nonhydrostatic, free-surface model (Mahadevan 2006), where the top layer of grid cells moves with the surface. The grid is stretched in the vertical for finer resolution near the free surface. The model is periodic in the meridional layer of grid cells moves with the surface. The grid is stretched in the vertical for finer resolution near the free surface. The model is periodic in the meridional stretched in the vertical for finer resolution near the bottom at 200 m. The model time step was 108 s. Hourly averaged wind stress computed from R/V Endeavor observations using the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) algorithm for 13–21 June was used in wind-forced runs.

REFERENCES


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THE DEEP CONVECTIVE CLOUDS AND CHEMISTRY (DC3) FIELD CAMPAIGN


DC3 brought together simultaneous measurements of storm kinematics, structure, electrical activity, and chemistry to improve our knowledge of how thunderstorms affect the chemical composition of the troposphere.

Thunderstorms over the central United States are a near-daily occurrence during the late spring and summer (e.g., Carbone et al. 2002). These storms range from airmass thunderstorms, to multicellular thunderstorms and supercells, to mesoscale convective systems (MCSs) depending on the instability, wind shear, and mesoscale forcing of the atmosphere. Many studies on thunderstorms have been concerned with predicting precipitation and severity of the storms for human welfare as well as understanding the formation of hail and lightning. However, convective storms can also have a widespread impact on upper-tropospheric (UT) composition over the United States and downwind over the western North Atlantic as discovered by previous field campaigns (e.g., Dickerson et al. 1987; Dye et al. 2000; Brunner et al. 1998; Crawford et al. 2000; Cooper et al. 2006; Bertram et al. 2007) and modeling studies (e.g., Chatfield and Crutzen 1984; Zhang et al. 2003; Li et al. 2005; Allen et al. 2010; Barth et al. 2012).

As trace gases and aerosols are transported from the boundary layer (BL) to the UT, several processes occur along the way affecting the constituents’ abundance. The redistribution of reactive chemical species by convective transport were theoretically recognized by Chatfield and Crutzen (1984) and observed for ozone (O₃), nitric oxide (NO), carbon monoxide (CO), and volatile organic compounds (VOCs) by Dickerson et al. (1987). Convective storms were also found to rain out highly soluble trace gases [e.g., nitric acid (HNO₃)] and hygroscopic aerosols (e.g., sulfate), while lightning was found to produce substantial amounts of nitrogen oxides (NOₓ = NO + NO₂; e.g., Ridley et al. 1994, 2004b). Estimating the convective transport and scavenging of partially soluble trace gases [e.g., formaldehyde (CH₂O), hydrogen peroxide (H₂O₂), and methyl hydroperoxide (CH₃OOH)] that are precursors for hydrogen oxides (HOₓ = OH + HO₂) and O₃ has proven to be challenging. The role of ice in the convective processing of these soluble...
trace gases is poorly understood (Barth et al. 2001, 2007a), while scattering of sunlight by cloud particles complicates photochemistry that occurs within and near the storm. UT trace gases affected by convective transport and lightning then undergo photochemistry, increasing ozone production in the UT by as much as a factor of 4 with peak net ozone production rates of 15 ppbv day⁻¹ as estimated by modeling studies (Pickering et al. 1990).

While several studies in the past 20 years have explored the influence of deep convection on the chemical composition of the upper troposphere (e.g., Pickering et al. 1996; Jaeglé et al. 1997; Ridley et al. 2004a,b; Singh et al. 2007; Huntrieser et al. 2002, 2007, 2008, 2009, 2011; Ancellet et al. 2009; Barret et al. 2010; Avery et al. 2010), there has not been a field experiment providing a comprehensive suite of airborne chemical composition measurements within the context of ground-based storm kinematic, microphysical, and lightning observations. In addition, none of these previous field experiments intentionally investigated the photochemical aging of the UT convective outflow by tracking the convective outflow from the thunderstorm to regions downwind.

The Deep Convective Clouds and Chemistry (DC3) field campaign utilized extensively instrumented aircraft platforms and ground-based observations to investigate the impact of deep, midlatitude continental convective clouds, including their dynamical, physical, and lightning processes, on UT composition and chemistry. The DC3 field campaign had two major goals:

1) quantify and characterize the convective transport of emissions and water to the upper troposphere within the first few hours of active convection, investigating storm dynamics and physics, lightning and its production of nitrogen oxides, cloud hydrometeor effects on scavenging of species, surface emission variability, and chemistry in the anvil, and

2) quantify the changes in chemistry and composition in the upper troposphere after active convection, focusing on 12–48 h after convection and the seasonal transition of the chemical composition of the UT.

**Context with previous studies.** Findings from previous studies of thunderstorms and chemistry motivated many of the DC3 objectives. Highlighted results from these previous campaigns are discussed here.

The 1996 Stratosphere-Troposphere Experiment: Radiation, Aerosols, and Ozone (STERAO-A) campaign, which sampled storms in northeast Colorado, used two aircraft, the University of North Dakota Citation and the National Oceanic and Atmospheric Administration (NOAA) P-3D, to sample the composition in the inflow and outflow regions of the storms. The Colorado State University (CSU)—University of Chicago–Illinois State Water Survey (CHILL) national radar facility and the Office National d’Études et Recherches Aérospatiales (ONERA) lightning interferometer array sampled storm kinematics and lightning, respectively. A detailed examination of the 10 and 12 July 1996 STERAO storms revealed that 1) intracloud (IC) lightning flashes can be a major...
contributor to NO\textsubscript{x}, [DeCaria et al. (2000)]; as opposed to earlier studies that claimed that NO\textsubscript{x} production per IC flash was 10% of the NO\textsubscript{x} production from a cloud-to-ground (CG) flash], 2) lightning occurred primarily in moderate updrafts and weak downdrafts (Dye et al. 2000), 3) production of NO from lightning was estimated to be 330–460 mol NO (4.6–6.5 kg N) per flash (DeCaria et al. 2005), and 4) cloud-scale modeling reasonably represented transport and redistribution of insoluble trace gases, but it was unknown how well they represented transport and scavenging of soluble gases (Barth et al. 2007b). Therefore, an objective of DC3 was to learn how much of the soluble trace gases that are precursors for O\textsubscript{3} production is transported to the UT in thunderstorms.

Two results from the 2000 Severe Thunderstorm Electrification and Precipitation Study (STEPS), which sampled storm and lightning characteristics in the high plains region of eastern Colorado and western Kansas by the first-generation lightning mapping array (LMA), polarimetric radar, storm-penetrating aircraft, and electric field meter soundings (Lang et al. 2004) motivated additional observations. Wiens et al. (2005) related storm parameters to total lightning flash rates rather than to only CG flash rates. Via modeling of a supercell, Kuhlman et al. (2006) found that trends in total flash rates were well correlated with trends in ice mass flux, volumes of updrafts greater than 10 m s\textsuperscript{-1}, and the volume of graupel. Thus, one objective of DC3 was to evaluate these and other relationships between lightning and storm properties for storms observed in a variety of regions. A second result from STEPS was the discovery that polarity of the charge distribution in the vertical was inverted from the polarity usually observed outside the high plains, with a large region of positive charge at midlevel and a large region of negative charge at upper levels (Rust and MacGorman 2002; Rust et al. 2005; MacGorman et al. 2005; Wiens et al. 2005; Tessendorf et al. 2007; Weiss et al. 2008; Bruning et al. 2014). Many of these storms produced predominantly positive CG flashes and were characterized as low-precipitation storms. In a statistical study of many storms, MacGorman et al. (2011) reported that storms observed during STEPS tended to require tens of minutes longer to produce a CG flash after producing their first flash than storms required outside the high plains and suggested that this delay was caused by the longer time needed to develop precipitation in the lower region of the storm. A better understanding of inverted-polarity storms was an objective of DC3 because they produce a larger-than-usual fraction of cloud lightning at higher altitudes, thereby impacting the vertical placement of lightning-NO\textsubscript{x} sources.
The Intercontinental Chemical Transport Experiment Phase A (INTEX-A) campaign used the National Aeronautics and Space Administration (NASA) DC-8 aircraft to sample the atmospheric composition over North America during July and August 2004. The results from INTEX-A showed a substantial influence of deep convection on UT composition. Bertram et al. (2007) estimated that 54% of UT air was influenced by convection that occurred during the previous 2 days. Snow et al. (2007) showed that convectively influenced air was enhanced in CH$_3$OOH, CH$_2$O, CO, NO, and NO$_2$ and depleted in H$_2$O$_2$ and HNO$_3$ compared to the background UT atmosphere. Singh et al. (2007) and Hudman et al. (2007, 2009) found that the influence of lightning on NO$_x$ in the UT was approximately 4 times greater than expected by global models. These intriguing results from INTEX-A motivate further research to understand the storm processes affecting convective transport of trace gases, to better follow the chemical evolution of UT convective outflow to quantify O$_3$ production, and to examine the vertical extent of the impact by convection on the UT composition. These were all objectives of DC3.

The African Monsoon Multidisciplinary Analysis (AMMA) campaign in 2006 in western Africa used several aircraft (French Falcon, French ATR-42, German DLR Falcon, UK BAe-146) to sample the composition of the BL and UT near convective storms, while radars sampled the storm structure and kinematics, and the very low-frequency/low-frequency lightning detection network (LINET) detected lightning flashes. Huntrieser et al. (2011) studied two mesoscale convective systems and determined the production of NO from lightning to be 70–180 mol NO per flash. These lightning-NO$_x$ production estimates are similar to findings from other tropical studies but smaller than the 300–500 mol per flash estimated for midlatitude storms (Schumann and Huntrieser 2007). Note that 100 mol NO is equivalent to 3 kg NO or 1.4 kg N. This significant difference of LNO$_x$ production between the midlatitudes and tropics calls for better understanding of the storm processes affecting LNO$_x$ production and exploring whether other flash characteristics (e.g.,
flash extent) contribute to the LNO$_3$ production. Such information is vital for refining estimates for the global production of NO from lightning, which is currently accepted to be 5 ± 3 Tg N annually (Schumann and Huntrieser 2007).

**EXPERIMENTAL DESIGN.** *Overall experimental design.* To address the first DC3 goal of characterizing the impact of deep convective storms on the chemical environment, aircraft were deployed to sample trace gases, aerosols, and meteorological properties in the inflow and outflow regions of the thunderstorms (Fig. 1). Ground-based radar networks, LMAs, and weather balloons obtained data on storm kinematics and structure, lightning, and storm thermodynamic environment. When multiple aircraft were sampling one storm, one aircraft, usually the NASA DC-8, was placed in the inflow region, while the second, usually the National Center for Atmospheric Research (NCAR) Gulfstream V (GV) aircraft, was placed in the outflow region of the storm. After characterizing the BL, the DC-8 aircraft often ascended to the anvil and sampled the outflow region to connect inflow and outflow for the variables measured aboard the DC-8 that were not sampled by the other aircraft (primarily aerosol properties and HOx mixing ratios). The DLR Falcon aircraft sampled the outflow region—however, closer to the convective core and frequently separated in time (few hours) and space (other cells of a larger convective system) compared to the storms investigated by the GV and DC-8.

*Storms in three regions* (Fig. 2)—northeast Colorado, central Oklahoma to west Texas, and northern Alabama—were sampled by aircraft deployed from an operations base in Salina, Kansas. The sampling regions were chosen because 1) they all have ample ground-based facilities, 2) the likelihood of convection occurring in one of the three locations increases the chances of successful flight operations on any given day, and 3) the three regions have different storm properties and chemical composition environments. The DC3 principal investigators’ (PIs’) goal was to have four cases sampled by aircraft in each of the three regions, thus allowing an even distribution of different storm properties and chemical environments for analysis. Details describing the three regions are given below.

To determine the probability of thunderstorms at each sampling region and to predict the location of the UT convective outflow plume 12–48 h after active convection, several high-resolution Weather Research and Forecasting (WRF) Model forecasts were conducted. The NCAR research-grade 48-h WRF forecasts at 3-km grid spacing were produced twice a day (0000 and 1200 UTC), with the initial conditions supplied by a continuously cycling ensemble Kalman filter analysis–forecast system with 15-km horizontal grid length, using the
Table 1. Characteristics of the radars used during DC3.

<table>
<thead>
<tr>
<th>Radar</th>
<th>Detects</th>
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<tr>
<td><strong>Colorado</strong></td>
<td></td>
</tr>
<tr>
<td>CSU–CHILL S band</td>
<td>Precipitating particles, Doppler velocity, clear air returns, and hydrometeor identification (i.e., polarimetric)</td>
</tr>
<tr>
<td>CSU-Pawnee S band</td>
<td>Precipitating particles, Doppler velocity, clear air returns, and hydrometeor identification (i.e., polarimetric)</td>
</tr>
<tr>
<td>NVS WSR-88D KFTG</td>
<td>Reflectivity of precipitating particles and Doppler velocity</td>
</tr>
<tr>
<td>NVS WSR-88D KCYS</td>
<td>Reflectivity of precipitating particles and Doppler velocity</td>
</tr>
<tr>
<td><strong>Oklahoma–Texas</strong></td>
<td></td>
</tr>
<tr>
<td>NOAA MPAR S band</td>
<td>Reflectivity of precipitating particles and Doppler velocity</td>
</tr>
<tr>
<td>NOAA NOXP X band</td>
<td>Precipitating particles, Doppler velocity, clear air returns, and hydrometeor identification (i.e., polarimetric)</td>
</tr>
<tr>
<td>OU SMART 1 C band</td>
<td>Reflectivity of precipitating particles and Doppler velocity</td>
</tr>
<tr>
<td>OU SMART 2 C band</td>
<td>Precipitating particles, Doppler velocity, clear air returns, and hydrometeor identification (i.e., polarimetric)</td>
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<tr>
<td>OU KOUN S band</td>
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<tr>
<td>NVS WSR-88D KTLX</td>
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<tr>
<td>NVS WSR-88D KFDR</td>
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<tr>
<td>NVS WSR-88D KLBB</td>
<td>Reflectivity of precipitating particles and Doppler velocity</td>
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<td>NVS WSR-88D KAMA</td>
<td>Precipitating particles, Doppler velocity, clear air returns, and hydrometeor identification (i.e., polarimetric)</td>
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<td>NVS WSR-88D KVNX</td>
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<tr>
<td><strong>Alabama</strong></td>
<td></td>
</tr>
<tr>
<td>UAH ARMOR C band</td>
<td>Precipitating particles, Doppler velocity, clear air returns, and hydrometeor identification (i.e., polarimetric)</td>
</tr>
<tr>
<td>UAH MAX X band</td>
<td>Precipitating particles, Doppler velocity, clear air returns, and hydrometeor identification (i.e., polarimetric)</td>
</tr>
<tr>
<td>NVS WSR-88D KHTX</td>
<td>Precipitating particles, Doppler velocity, clear air returns, and hydrometeor identification (i.e., polarimetric)</td>
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</tbody>
</table>

single member closest to the ensemble mean for each forecast (Schwartz et al. 2014; Romine et al. 2014). These forecasts included boundary layer and lightning-NOx tracers to predict the location of the downwind outflow. Twenty-four-hour Flexible Particle (FLEXPART) dispersion model (Stohl et al. 2005) forecasts were performed from the location of the convective outflow air in the UT where the aircraft sampled to identify more precisely the location of the downwind plume 20–24 h later. To aid finding the downwind plume, high NO2 column densities sampled by the morning overpass of the Global Ozone Monitoring Experiment-2 (GOME-2) satellite instrument were used. The global-scale Model for Ozone and Related Chemical Tracers (MOZART) gases (Emmons et al. 2010), Regional Air Quality Modeling System (Pierce et al. 2007), and FLEXPART gave information on the context of the chemical environment including information on species from biomass burning and long-range transport. A lead forecaster located at the operations base led the weather forecasting for the day’s storm activity, but regional forecasters based at CSU, NOAA/National Severe Storms Laboratory (NSSL) and University of Oklahoma (OU), and the University of Alabama in Huntsville (UAH) gave detailed, local forecasts. A probabilistic forecasting system was used to aid the decision process.
Fig. 4. The Oklahoma–Texas ground network configuration. The red squares are the SMART radars and the blue square is the NWS KOUN radar. The purple squares locate the LMA stations and the yellow dots locate the mesonet stations. The purple circles denote the LMA coverage with 300-m location error. The green circles are the dual-Doppler and polarimetric radar coverage.

for suitable flight conditions and optimum use of flight hours (Hanlon et al. 2014). To ensure the safety of the aircraft, nowcasters at the operations base provided weather updates during flight operations.

We found that the logistical setup worked well for DC3 operations for deploying aircraft to one of three locations. A key part of this success was the centralized operations base where the PIs, lead weather forecaster, and aircraft mission scientists could discuss plans in person. The facilities at Salina were optimal for this, accommodating multiple aircraft and over 200 people in one building. Equally valuable were the Internet-based communications via the field catalog, the tracking of the aircraft and weather during flights, and the aircraft–ground communications that allowed real-time maneuvering as new opportunities appeared. Thus, the preparations for the campaign’s physical and computing facilities were crucial.

Colorado. The DC3 northeast Colorado region roughly encompasses the area from Denver, Colorado, to Cheyenne, Wyoming, over the high-elevation plains and foothills of the mountains (Fig. 3). The CSU–CHILL S-band Doppler and polarimetric radar (Table 1), located in Greeley, Colorado, was the primary radar used in DC3. Located 45 km to the north is the CSU–Pawnee S-band radar. These two radars formed a dual-Doppler pair providing characterization of 3D winds in precipitation. Two Weather Surveillance Radar-1988 Doppler (WSR-88D) radars—one near Denver and the second in Cheyenne—complemented this dual-Doppler pair, extending dual-Doppler coverage from southeastern Wyoming to just south of Denver. The radar data included three-dimensional winds and precipitation and hydrometeor identification fields from CSU–CHILL.

The Colorado lightning mapping array (COLMA; Rison et al. 1999; Lang et al. 2014) consisted of 15 stations detecting very high-frequency (VHF) sources providing lightning locations and lightning channel geometries throughout the region mapped by the dual-Doppler radar pairs. The NCAR Mobile Integrated Sounding System launched radiosondes before and during storms to obtain vertical profiles of environmental temperature, pressure, relative humidity, and winds.
The Colorado ground-based facilities sampled 16 case studies, including 3 days where electrified fire plumes were studied (Lang et al. 2014). The aircraft sampled storms in northeast Colorado for 8 days. Six of those flights were coordinated with the CSU–CHILL and CSU-Pawnee radars, and two flights, in eastern Colorado, were coordinated with the Oklahoma mobile radars, which are described in the next section.

Oklahoma and Texas. The DC3 central Oklahoma to west Texas region extends from the New Mexico border west of Lubbock, Texas, to northeast of Oklahoma City, Oklahoma (Fig. 4). Radars for the Oklahoma–Texas venue included both fixed site and mobile facilities (Table 1). The fixed radars were the WSR-88D Doppler radars at Oklahoma City, Frederick, and Vance Air Force Base in Oklahoma; Lubbock and Amarillo, Texas; and in Norman, Oklahoma, two S-band radars [KOUN and the multifunction phased array radar (MPAR)]. The available mobile radars were the NOAA/NSSL X-band polarimetric (NOXP) radar and the two C-band Shared Mobile Atmospheric Research and Teaching (SMART) radars (SR1 and SR2; Biggerstaff et al. 2005).

The Oklahoma Lightning Mapping Array (OKLMA; MacGorman et al. 2008) includes 11 stations in central Oklahoma and 7 stations in southwest Oklahoma (Fig. 4). The West Texas LMA (WTLMA) has 11 stations near Lubbock. NSSL launched radiosondes before and during storms to obtain vertical profiles of environmental thermodynamic parameters. This system also was used for larger balloons carrying instruments inside storms (Rust et al. 1999) to measure the vector electric field and to provide precipitation imaging along the balloon track.

The Oklahoma radar and sounding units operated on 13 days during the DC3 field campaign. On seven of those days, in-storm electric field measurement soundings were successfully launched into storms. In coordination with the ground facilities, the DC-8 and GV aircraft sampled five cases in the Oklahoma–Texas region, while the Falcon aircraft sampled three additional cases.

Alabama. The DC3 Alabama operations area (Fig. 5) included northern Alabama and southern Tennessee. The ground-based operations included the Advanced Radar for Meteorological and Operational Research (ARMOR) C-band radar, located at the Huntsville International Airport, the truck-based Mobile Alabama X-band (MAX) radar, deployed at a fixed site near New Market, Alabama, 42.5 km northeast of ARMOR, and the WSR-88D Doppler radar, located 34.9 km east of MAX and 70.3 km northeast of ARMOR (Table 1). The three radars provide high temporal- and spatial-resolution polarimetric, multi-Doppler observations of storm microphysics and kinematics over the Northern Alabama Lightning Mapping Array (NA-LMA) domain. The NASA Marshall Space Flight Center (MSFC)-owned
Table 2. Payload for the National Science Foundation (NSF)–NCAR GV during DC3. a OVOC = organic VOC. VUV = vacuum ultraviolet. CRDS = cavity ring-down spectroscopy. GC/MS = gas chromatography–mass spectrometry. CIMS = chemical ionization mass spectrometer. IR = infrared. TDL = tunable diode laser.

<table>
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<tr>
<th>Instrument</th>
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<th>Method</th>
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<td>CARI&lt;sup&gt;b&lt;/sup&gt; O&lt;sub&gt;3&lt;/sub&gt;</td>
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<tr>
<td>CO</td>
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<td>PICARRO</td>
<td>CARI CO&lt;sub&gt;2&lt;/sub&gt;, CH&lt;sub&gt;4&lt;/sub&gt;</td>
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<td>Apel VOCs, OVOCs, halocarbons</td>
<td>GC/MS</td>
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<td>Huey HNO&lt;sub&gt;3&lt;/sub&gt;, HNO&lt;sub&gt;4&lt;/sub&gt;, SO&lt;sub&gt;2&lt;/sub&gt;, HCl</td>
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<td>CAMS</td>
<td>Fried CH&lt;sub&gt;2&lt;/sub&gt;O</td>
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<td>Zondlo H&lt;sub&gt;2&lt;/sub&gt;O vapor</td>
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<td>RAF&lt;sup&gt;c&lt;/sup&gt; Aerosol number</td>
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<td>RAF Cloud particle imager 10–1280 μm</td>
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<tr>
<td>Aircraft</td>
<td>RAF Basic meteorological and aircraft state data</td>
<td>Various</td>
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<tr>
<td>DV</td>
<td>RAF Video images</td>
<td>Digital cameras</td>
</tr>
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<sup>a</sup>A description of the instruments can be found at www-air.larc.nasa.gov/cgi-bin/ArcView/dc3/GV=1.

<sup>b</sup>The Community Airborne Research Instrumentation (CARI) team is Flocke, Weinheimer, Knapp, Montzka, and Campos.

<sup>c</sup>RAF is the Research Aviation Facility at NCAR.

and operated NA-LMA is composed of 11 stations over northern Alabama that are supplemented by two Georgia Institute of Technology sensors located near Atlanta, Georgia (Goodman et al. 2005).

The UAH sounding system launched weather radiosondes in the preconvective, inflow proximity, and postconvective environments on aircraft operations days. The Mobile Integrated Profiling System (MIPS), based at UAH, includes a 915-MHz Doppler wind profiler, X-band profiling radar, microwave profiling radiometer, lidar ceilometer, and a host of standard meteorological sensors to obtain BL and precipitation measurements. MIPS was sometimes deployed to a favored multi-Doppler lobe sampling the preconvective to postconvective environment for constraining the microphysical and kinematic retrievals from the scanning radars.

Twelve cases, including a variety of thunderstorms, were sampled by the ground operations in the northern Alabama region. Two cases were MCSs that occurred at night—a time when aircraft sampling did not occur because of safety considerations. The DC-8 and GV aircraft sampled two of the Alabama cases in coordination with the ground operations, while the Falcon aircraft did not sample any Alabama storms.

**Aircraft.** The NCAR GV aircraft sampled storms and aged convective outflow from 18 May to 30 June, while the NASA DC-8 collected data from 18 May to 22 June. The DLR Falcon conducted research flights from 29 May to 14 June. The GV aircraft measured a suite of trace gases, actinic and irradiance fluxes, aerosol number and their size distributions, and cloud water and ice size distributions (Table 2). The DC-8 aircraft sampled many of these same parameters but also measured the aerosol composition and optical properties (Table 3). Unique to the DC-8 aircraft were measurements of the primary oxidants, OH and...
<table>
<thead>
<tr>
<th>Instrument</th>
<th>PI</th>
<th>Species/parameter</th>
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<td>NO, NO₂, NO₃, O₃</td>
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<td>Diskin</td>
<td>CO, CH₄, N₂O</td>
<td>TDL spectroscopy</td>
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<td>Beyersdorf</td>
<td>CO&lt;sub&gt;j&lt;/sub&gt;</td>
<td>Differential NDIR</td>
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<td>Huey</td>
<td>PAN, PPn, HNO₃, SO₂, HCl</td>
<td>CIMS</td>
</tr>
<tr>
<td>CIT-CIMS&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Wennberg</td>
<td>H₂O₂, CH₂OOH, HNO₃, C₅H₈O₃, C₆H₈O₃, ETHLN, GLYC, HAC, HCN, IEPOX, ISOPN, ISOPOOH, PAA, PROPNN</td>
<td>CIMS</td>
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<td>DFGAS</td>
<td>Fried</td>
<td>CH₂O</td>
<td>IR laser spectroscopy</td>
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<td>ISAF</td>
<td>Hanisco</td>
<td>CH₂O</td>
<td>LIF</td>
</tr>
<tr>
<td>SAGA</td>
<td>Dibb, Weber</td>
<td>HNO₃, fine-particle SO₄, brown carbon</td>
<td>MC/IC, filters</td>
</tr>
<tr>
<td>ATHOS</td>
<td>Brune</td>
<td>OH, HO₂</td>
<td>LIF</td>
</tr>
<tr>
<td>BBR</td>
<td>Bucholtz</td>
<td>Broadband solar and IR</td>
<td>Radiometers</td>
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<tr>
<td>SSFR</td>
<td>Schmidt</td>
<td>Spectral solar irradiance</td>
<td>Solar spectral flux radiometer</td>
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<td>PI-Neph</td>
<td>Martins</td>
<td>Aerosol phase function and scattering coefficient</td>
<td>PI nephelometer</td>
</tr>
<tr>
<td>CAFS</td>
<td>Hall</td>
<td>Actinic flux</td>
<td>Collection, dispersion spectroscopy</td>
</tr>
<tr>
<td>DLH</td>
<td>Diskin</td>
<td>H₂O vapor</td>
<td>TDL spectroscopy</td>
</tr>
<tr>
<td>LARGE</td>
<td>Anderson</td>
<td>Aerosol number concentration, size distribution (0.01–5 μm), and optical properties</td>
<td>CPC, optical and mobility particle sizers, nephelometry, absorption photometry</td>
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<tr>
<td>CCN</td>
<td>Nenes</td>
<td>CCN concentration</td>
<td>DMT CCN</td>
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<tr>
<td>AOP</td>
<td>Brock</td>
<td>Aerosol size distribution, aerosol absorption, extinction</td>
<td>UHSAS, PAS, CRD aerosol extinction spectrometer</td>
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<tr>
<td>DASH</td>
<td>Sorooshian</td>
<td>Aerosol hygroscopic growth factor</td>
<td>DASH-SP</td>
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<tr>
<td>PALMS</td>
<td>Froyd</td>
<td>Single-particle chemical composition</td>
<td>Laser mass spectrometry</td>
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<tr>
<td>HD-SP2</td>
<td>Gao</td>
<td>Black carbon mass, hygroscopicity</td>
<td>Humidified dual single-particle photometer</td>
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<tr>
<td>AMS</td>
<td>Jimenez</td>
<td>Chemically speciated submicron particulate mass</td>
<td>TOF-AMS</td>
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<tr>
<td>DIAL HSRL</td>
<td>Hair</td>
<td>O₃ and aerosol profiles</td>
<td>Lidar</td>
</tr>
<tr>
<td>SPEC</td>
<td>Lawson</td>
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<td>2D-S</td>
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<tr>
<td>MMS</td>
<td>Bui</td>
<td>Pressure, temperature, 3D winds</td>
<td>Various</td>
</tr>
<tr>
<td>Aircraft</td>
<td>NASA Airborne Science Program</td>
<td>Basic meteorological and aircraft state data</td>
<td>Digital cameras</td>
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</table>

<sup>a</sup> A description of the instruments can be found at [www-air.larc.nasa.gov/cgi-bin/ArcView/dc3-seac4rs](http://www-air.larc.nasa.gov/cgi-bin/ArcView/dc3-seac4rs).

<sup>b</sup> TD-LIF = thermal-dissociation laser-induced fluorescence. NDIR = nondispersive infrared spectrometer. PTR-MS = proton-transfer-reaction mass spectrometer. GC = gas chromatography. PI = polarized imaging. MC/IC = mist chamber/ion chromatograph. CPC = condensation particle counter. CCN = cloud condensation nuclei. DMT = Droplet Measurement Technologies. UHSAS = ultra-high sensitivity aerosol spectrometer. PAS = photoacoustic spectrometer. CRD = cavity ring down. DASH-SP = differential aerosol sizing and hygroscopicity spectrometer probe. TOF-AMS = time-of-flight aerosol mass spectrometer. 2D-S = two-dimensional stereo.

<sup>c</sup> MPN = methyl peroxy nitrate, PN = peroxy nitrates, AN = alkyl nitrates.

<sup>d</sup> C₅H₁₀O₃ = dihydroxy isoprene epoxides, C₆H₈O₃ = isoprene hydroxyperoxyaldehydes, ETHLN = ethanal nitrate, GLYC = glycolaldehyde, HAC = hydroxyacetone, HCN = hydrogen cyanide, IEPOX = isoprene epoxides, ISOPN = isoprene hydroxynitrates, ISOPOOH = isoprene hydroxyperoxides, PAA = peroxyacetic acid, PROPNN = propanone nitrate.
Table 4. Payload for the DLR Falcon during DC3.* UV = ultraviolet. GC/FID = gas chromatography with flame ionization detection. CN = condensation nuclei.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>PI</th>
<th>Species/parameter</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE49C</td>
<td>Schlager</td>
<td>O$_3$</td>
<td>UV absorption</td>
</tr>
<tr>
<td>SR1</td>
<td>Schlager</td>
<td>NO</td>
<td>Chemiluminescence</td>
</tr>
<tr>
<td>SR2</td>
<td>Schlager</td>
<td>Total reactive nitrogen (NO$_y$)</td>
<td>Au-reduction converter + chemiluminescence</td>
</tr>
<tr>
<td>Aerolaser</td>
<td>Schlager</td>
<td>CO</td>
<td>VUV fluorescence</td>
</tr>
<tr>
<td>PICARRO</td>
<td>Schlager</td>
<td>CO$_2$, CH$_4$</td>
<td>CRDS</td>
</tr>
<tr>
<td>Canisters</td>
<td>Rappenglueck</td>
<td>VOCs</td>
<td>GC/FID</td>
</tr>
<tr>
<td>CI-ITMS</td>
<td>Aufmhoff</td>
<td>SO$_2$, HNO$_3$</td>
<td>CIMS</td>
</tr>
<tr>
<td>Multichannel CPC</td>
<td>Minikin</td>
<td>Total and nonvolatile CN concentration</td>
<td>Condensation particle counter with/without thermal denuder</td>
</tr>
<tr>
<td>OPC (Grimm)</td>
<td>Minikin</td>
<td>Aerosol number concentration and size (0.25–2 $\mu$m)</td>
<td>Optical scattering</td>
</tr>
<tr>
<td>FSSP100</td>
<td>Minikin</td>
<td>Cloud particle number concentration and size (2–50 $\mu$m)</td>
<td>Optical scattering</td>
</tr>
<tr>
<td>UHSAS</td>
<td>Minikin</td>
<td>Aerosol particle number concentration and size (60 nm–1 $\mu$m)</td>
<td>Optical scattering</td>
</tr>
<tr>
<td>PCASP</td>
<td>Minikin</td>
<td>Aerosol particle number and size (0.1–3 $\mu$m)</td>
<td>Optical scattering</td>
</tr>
<tr>
<td>PCAP</td>
<td>Minikin</td>
<td>Soot absorption</td>
<td>Light attenuation through a filter</td>
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<tr>
<td>SP-2</td>
<td>Weinzierl</td>
<td>Black carbon mass</td>
<td>Single-particle photometry</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Zoeger</td>
<td>Basic meteorological and aircraft state data</td>
<td>Various</td>
</tr>
</tbody>
</table>

*A description of the instruments can be found at [www-air.larc.nasa.gov/cgi-bin/ArcView/dc3?FALCON=1].

HO$_2$, and the differential absorption lidar (DIAL) that obtained profiles of aerosol extinction and ozone. The Falcon aircraft obtained measurements of key trace gases and aerosols (Table 4). All three aircraft sampled several of the same species, including O$_3$, CO, CO$_2$, CH$_4$, VOCs, and NO. The NCAR GV and NASA DC-8 both sampled NO$_2$; a range of soluble trace gases including HNO$_3$, H$_2$O$_2$, CH$_2$O, and CH$_3$OOH; as well as biomass-burning (BB) tracers (e.g., CH$_3$CN and HCN). By flying two of the aircraft wingtip to wingtip for several minutes at different altitudes, the agreement between the instrument measurements could be evaluated. The NASA DC-8 and DLR Falcon conducted one intercomparison, while the NASA DC-8 and NCAR GV had five intercomparisons during the campaign.

Of the 20 storms that were sampled by the three aircraft, 11 storms were sampled in a coordinated fashion by the GV and DC-8 aircraft and the ground facilities. Measurements in 3 of these 11 storms were collected by all three aircraft in a coordinated fashion. The GV and DC-8 aircraft sampled the aged convective outflow of five of the storms that were sampled the previous day, while the DLR Falcon sampled aged convective outflow during one flight. A highlight photochemical-aging study was the 21 June 2012 case where first the DC-8, then the GV, sampled the convective outflow of a decaying MCS.

**STORM AND CHEMICAL ENVIRONMENTS OF THE THREE REGIONS.** By targeting storms in three regions of the United States, different storm types and different chemical environments were sampled. Here, we contrast the storm and chemical environments of the three regions.

The DC3-sampled thunderstorms over the high plains of northeast Colorado are predominantly shear-organized storms with moderate to high convective available potential energy (CAPE; Fig. 6). The low-level airflow is often from the southeast and upper-level flow is usually from the west. The Colorado storms have high cloud bases, because the warm and dry boundary layers in the region require higher-altitude lifting condensation levels, resulting in a smaller warm-cloud depth and a more vigorous mixed-phase region. The thunderstorms in Oklahoma and west Texas are primarily shear-organized storms, but some airmass storms (low vertical wind shear) can occur. Most storms observed in Alabama occurred in low vertical shear environments with low CAPE.
(<2000 J kg\(^{-1}\)) although shear-organized storms, associated with cold fronts, can occur in midspring.

The lightning characteristics of the three regions also varied because of their different storm environments. We expect lightning flash rate to correlate with CAPE and vertical wind shear based on previous studies that show a positive relation between CAPE and lightning flash rate (e.g., Williams et al. 1992, 2005; Gilmore and Wicker 2002; Qie et al. 2003). Previous work has also connected flash extent and vertical wind shear (Huntrieser et al. 2008). Here, we use the lightning flash density, which allows the flash rate to be normalized by the area where flashes are occurring. We calculate the lightning flash density by counting the number of flashes in a 3 × 3 km\(^2\) grid box for every 5-min time period (the flash rates are estimated by grouping individual VHF radiation bursts associated with lightning). From the collection of all grid boxes over the LMA region, we extract the 95th percentile values. The maxima of the 95th percentile shows that there are more than 2 flashes per kilometer per minute (flashes km\(^{-2}\) min\(^{-1}\)) in Colorado storms (Fig. 6) sampled by the aircraft except for the weak convection observed on 5 June. The lightning flash rate density is high (and higher than the other two DC3 regions) because of the high IC flash rates that commonly occur in the high plains (e.g., Boccippio et al. 2001). The storms in Oklahoma observed during DC3 by the aircraft and ground facilities had 1–2 flashes km\(^{-2}\) min\(^{-1}\), which is somewhat less than those found in Colorado (Fig. 6). In contrast, the two storms sampled in Alabama by the aircraft had lightning flash densities less than 0.5 flashes km\(^{-2}\) min\(^{-1}\). The storm flash rates in the Alabama storms were generally less than those found in the other two regions because of the different type of convection (low-shear, low-CAPE-producing smaller regions of graupel and lower supercooled water contents) in Alabama. While we conclude here that flash densities are greatest in the northeast Colorado region, storm-total flash rates in Oklahoma were similar to those in Colorado because the sizes of the sampled Oklahoma storms were often larger than those in Colorado.

The DC3 Colorado region comprises an urban corridor along with agriculture and ranching activities. Low-altitude aircraft measurements showed moderate to high anthropogenic VOCs but low biogenic VOCs except over the Rocky Mountain foothills. This relationship can be illustrated using toluene and isoprene to represent anthropogenic and biogenic VOCs, respectively (Fig. 7). To characterize the aerosols in the region, we use the dry aerosol extinction coefficient as a proxy for aerosol abundance and the organic aerosol fraction of the particulate matter smaller than 1 µm (PM1). The dry aerosol extinction coefficient represents the amount of radiation (for the instrument used here, at 532-nm wavelength) that is either scattered or absorbed by particles in the accumulation and coarse modes (which constitute nearly all the mass of the particles) at low relative humidity. Its units of per megameter (Mm\(^{-1}\), or 10\(^{-6}\) m\(^{-1}\)) can be related to the visible distance a human eye can see. Aerosol loadings in the northeast Colorado BL (Fig. 8) range from clean to typical values of 10–30 Mm\(^{-1}\) for rural areas (Andrews...
Fig. 7. The correspondence between average isoprene and toluene mixing ratios for the 0–2-km-altitude (AGL) range as measured by the DC-8 aircraft in the three sampling regions for all the aircraft storm cases except the 27 and 28 Jun Colorado cases, for which the GV measurements are used. The colors of the filled circles designate which region was sampled.

et al. 2011; Cai et al. 2011). The PM1 composition was mostly organic aerosol, while sulfate, nitrate, ammonium, and black carbon had smaller contributions.

Most of the Oklahoma–west Texas region is situated over the sparsely populated southern Great Plains where agriculture, pasture, and grassland dominate. However, the eastern part of the region has more scrub oak and forests, and central Oklahoma is affected by Oklahoma City and the outflow of the Dallas–Ft. Worth metropolitan area. Measurements of the boundary layer composition showed low to moderate biogenic VOCs and relatively low to moderately high anthropogenic VOCs (Fig. 7). Aerosol loadings were mostly 20–40 Mm⁻¹, which is slightly higher than typical rural levels of 10–30 Mm⁻¹ for dry aerosol extinction coefficient (Fig. 8). The contribution of BL organic aerosol to the PM1 composition was 45%–60% for all the Oklahoma–west Texas cases except for the 19 May 2012 case.

Northern Alabama–southern Tennessee is a forested area producing high levels of the biogenic VOC isoprene (Fig. 7). The area has regional anthropogenic influences and the city of Birmingham nearby produces moderate toluene levels and aerosol loadings (Fig. 8). The BL organic aerosol contribution to PM1 was approximately 40%. Sulfate had a larger contribution in this region compared to Colorado and Oklahoma–west Texas.

SELECTED CASES. The May–early June 2012 synoptic meteorology over the United States was characterized by troughs and ridges propagating from west to east, which is a typical pattern for the midlatitudes. The southern United States dried out and progressed into drought conditions during June owing to a stationary high pressure area over the region. Wildfires were abundant over the Rocky Mountain region (Johnson et al. 2014; Lang et al. 2014). In May, these wildfires were mostly in Arizona and New Mexico (Whitewater–Baldy fire). In June, most of the wildfires were in Colorado (notably the Hewlett Gulch and High Park fires near Ft. Collins), Utah, and Wyoming.

Table 5 lists all the DC3 cases with information on the weather and which aircraft facilities were operational. Five DC3 cases stand out as exceptional events to focus on. A storm case from each sampling region was selected to examine thunderstorm characteristics and trace-gas and aerosol redistribution. Two of these storms included a second-day sampling of their convective outflow to address goal 2. A second case from Colorado was chosen because of its isolated nature and its uniqueness in that the storm ingested a biomass-burning plume at about 7-km altitude. To understand the photochemical aging of fresh convective outflow, a decaying mesoscale convective system case was selected. These five cases are described briefly here. In addition to the weather scenario, lightning data and vertical profiles of trace gases are presented. The lightning data time series discussed for each case are the total flash rates for the storm in the DC3 target region, which frequently encompassed multiple cells and evolved with time to remain with those cells. Also reported are the average and standard deviation of the flash extent estimated from the square root of the area of a polygon drawn around each flash (Bruning and MacGorman 2013). In other, more detailed studies
Fig. 8. The correspondence between average dry aerosol extinction (Mm⁻¹) and mass concentration ratio of organic aerosol (OA) to PM1 (=sulfate + organic + nitrate + ammonium + chlorine + black carbon) aerosols for the 0–2-km-altitude (AGL) range as measured by the DC-8 aircraft in the three sampling regions. The colors of the filled circles designate which region was sampled, and the shaded region represents typical rural values of dry aerosol extinction.

(e.g., Bain 2013), these lightning data are found to be correlated with storm microphysics parameters (e.g., graupel volume) and with the estimated production of NOₓ from lightning to learn what storm characteristics are important to lightning and how the horizontal and vertical placement of lightning affects lightning NOₓ. The vertical profiles are data combined from the two or three aircraft sampling the storm and averaged into 0.5-km bins. CO, toluene, isoprene, and O₃ are shown to illustrate convective transport of gases in the thunderstorm environment. As very soluble species, HNO₃ and H₂O₂ vertical profiles should indicate scavenging by the storm. CH₂O is shown because it is an important source of HOₓ radicals, yet has complicated behavior in storms because it is moderately soluble and photochemically reactive. NOₓ vertical profiles indicate the importance of lightning as a NOₓ source by comparing mixing ratios in the UT to those in the BL. The 10% and 90% mixing ratios for CO, CH₂O, and NOₓ in the UT are also shown to contrast convective outflow (90% values) with UT background (10% values). Detailed analysis of convective transport, scavenging, production of NOₓ by lightning, and photochemistry will be presented in future publications on DC3.

**Weak convection case.** The synoptic weather on 21 May 2012 began with a weak cold front extending southward from Michigan through the Mississippi River valley and then westward as a stationary front through northern Texas. Convection occurred in the early morning in northern Alabama and Mississippi. By early afternoon, extensive convection formed in weak shear and low instability along a prefrontal trough in Tennessee, northern Alabama, and Mississippi as the cold front moved southward to the Gulf Coast states. An isolated thunderstorm developed in southern Tennessee, within the northern dual-Doppler lobes (Fig. 9), and was targeted for sampling by the DC-8 and GV aircraft as well as the ground-based LMA, radar, and sounding units. This prefrontal convection had updrafts of 10–20 m s⁻¹, creating a small graupel region (Bain 2013). Flash rates in the northern Alabama region peaked at 8 flashes per minute (Fig. 10a). The mean flash extent for this thunderstorm was 8–12 km and showed a tendency to have larger flashes when the flash rate was low and vice versa (Fig. 10a). The anti-correlation of flash extent and flash rate indicates that when the flash rate is high the charge centers are more compact and are near strong updrafts (Bruning and MacGorman 2013). This isolated thunderstorm occurred in a region of high BL VOCs (isoprene reached a few parts per billion by volume and CH₂O reached approximately 2.5 ppbv) and low BL NOₓ (~50 pptv). By comparing the outflow region in the UT (defined at altitudes between 7 km and the tropopause) to the BL (altitudes below 2.5 km), we find signatures of convective transport with CO enhanced by about 20 ppbv (Fig. 10b), scavenging of soluble gases, as indicated by suppressed H₂O₂ and CH₂O mixing ratios in the UT region compared to the BL (Figs. 10c,d) and lightning production of NOₓ with UT NOₓ reaching over 900 pptv (Fig. 10d). However, there was no pronounced enhancement of toluene and isoprene in the UT region compared to the BL likely because of the short chemical lifetimes of these VOCs.
<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Aircraft</th>
<th>Storm targeted</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 May</td>
<td>CO</td>
<td>DC-8, GV</td>
<td>High plains convection in vicinity of a front</td>
<td>Anthropogenic VOC sampling in BL</td>
</tr>
<tr>
<td>19 May</td>
<td>OK</td>
<td>DC-8, GV</td>
<td>Line of supercell convection in western Oklahoma</td>
<td>—</td>
</tr>
<tr>
<td>21 May</td>
<td>AL</td>
<td>DC-8, GV</td>
<td>Weak, prefrontal convection</td>
<td>—</td>
</tr>
<tr>
<td>25 May</td>
<td>OK</td>
<td>DC-8, GV</td>
<td>Supercell/prefrontal convection</td>
<td>—</td>
</tr>
<tr>
<td>26 May</td>
<td>IL</td>
<td>DC-8, GV</td>
<td>Downwind convection at Oklahoma–Texas Panhandle</td>
<td>—</td>
</tr>
<tr>
<td>29 May</td>
<td>OK</td>
<td>DC-8, GV, Falcon</td>
<td>Supercell/MCS in northern Oklahoma</td>
<td>—</td>
</tr>
<tr>
<td>29 May</td>
<td>TX</td>
<td>Falcon</td>
<td>Biomass-burning plume</td>
<td>—</td>
</tr>
<tr>
<td>30 May</td>
<td>TN–NC</td>
<td>DC-8, GV</td>
<td>Downwind flight</td>
<td>Intercomparison flight legs</td>
</tr>
<tr>
<td>30 May</td>
<td>TX</td>
<td>Falcon</td>
<td>Supercells</td>
<td>—</td>
</tr>
<tr>
<td>1 Jun</td>
<td>CO, TX</td>
<td>DC-8, GV</td>
<td>Multicells in TX Panhandle</td>
<td>Anthropogenic VOC sampling in BL</td>
</tr>
<tr>
<td>2 Jun</td>
<td>CO</td>
<td>DC-8</td>
<td>Isolated convection and squall line</td>
<td>—</td>
</tr>
<tr>
<td>5 Jun</td>
<td>CO</td>
<td>DC-8, GV</td>
<td>Weak isolated mountain storm</td>
<td>Aged convective outflow in region</td>
</tr>
<tr>
<td>5 Jun</td>
<td>TX</td>
<td>Falcon</td>
<td>Convection associated with a mesoscale convective vortex</td>
<td>Aged convective outflow in CO–KS</td>
</tr>
<tr>
<td>6 Jun</td>
<td>OK</td>
<td>None</td>
<td>Squall line</td>
<td>—</td>
</tr>
<tr>
<td>6 Jun</td>
<td>CO</td>
<td>DC-8, GV, Falcon</td>
<td>Convection associated with Denver cyclone</td>
<td>—</td>
</tr>
<tr>
<td>7 Jun</td>
<td>IL–MO</td>
<td>DC-8, GV</td>
<td>Downwind flight</td>
<td>Biogenic VOC sampling in BL</td>
</tr>
<tr>
<td>7 Jun</td>
<td>CO</td>
<td>None</td>
<td>Isolated supercells</td>
<td>—</td>
</tr>
<tr>
<td>8 Jun</td>
<td>KS–MO</td>
<td>Falcon</td>
<td>Aged anvil outflow of storms previously in Colorado</td>
<td>—</td>
</tr>
<tr>
<td>11 Jun</td>
<td>AL</td>
<td>DC-8, GV</td>
<td>Weak isolated storm</td>
<td>—</td>
</tr>
<tr>
<td>11 Jun</td>
<td>MO–AR</td>
<td>DC-8, GV, Falcon</td>
<td>MCS</td>
<td>DC-8 and Falcon intercomparison</td>
</tr>
<tr>
<td>12 Jun</td>
<td>CO–KS</td>
<td>Falcon</td>
<td>Multicell convection</td>
<td>—</td>
</tr>
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<td>14 Jun</td>
<td>KS</td>
<td>Falcon</td>
<td>Aged outflow</td>
<td>—</td>
</tr>
<tr>
<td>15 Jun</td>
<td>CO</td>
<td>DC-8, GV</td>
<td>Multicell cluster over Denver BB plume sampling</td>
<td>—</td>
</tr>
<tr>
<td>16 Jun</td>
<td>TX–OK</td>
<td>DC-8, GV</td>
<td>Multicell convection and MCS</td>
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<tr>
<td>17 Jun</td>
<td>LA, TX</td>
<td>DC-8, GV</td>
<td>Downwind flight</td>
<td>Intercomparison profile</td>
</tr>
<tr>
<td>21 Jun</td>
<td>MO</td>
<td>DC-8, GV</td>
<td>Dissipating MCS</td>
<td>Photochemical aging</td>
</tr>
<tr>
<td>22 Jun</td>
<td>CO</td>
<td>DC-8, GV</td>
<td>Isolated supercells</td>
<td>BB plume ingested into storm</td>
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<tr>
<td>23 Jun</td>
<td>AR–TN</td>
<td>GV</td>
<td>Downwind flight</td>
<td>—</td>
</tr>
<tr>
<td>25 Jun</td>
<td>Gulf of Mexico</td>
<td>GV</td>
<td>Aged outflow</td>
<td>—</td>
</tr>
<tr>
<td>27 Jun</td>
<td>CO</td>
<td>GV</td>
<td>Weakly organized storms associated with a cold front</td>
<td>—</td>
</tr>
<tr>
<td>28 Jun</td>
<td>CO</td>
<td>GV</td>
<td>Disorganized, widespread storms</td>
<td>—</td>
</tr>
<tr>
<td>30 Jun</td>
<td>KS, TX</td>
<td>GV</td>
<td>No storms; partly cloudy skies</td>
<td>Anthropogenic VOC sampling in BL</td>
</tr>
</tbody>
</table>
**Severe convection case.** The 29 May 2012 Oklahoma case was composed of a line of isolated supercell storms from northern through central Oklahoma that produced strong winds, large hail, and an enhanced Fujita scale 1 (EF1) tornado. The morning weather showed a cold front stretching from the Ohio Valley southward and arcing back into northern Oklahoma and southern Kansas. Ahead of the front and dryline, which was positioned in extreme western Texas and eastern New Mexico in the morning, the atmosphere was very unstable. By 2100 UTC, storms had initiated in northwest Oklahoma. These storms subsequently developed into a line of initially isolated supercells (Fig. 11). The GV sampled the UT convective outflow, with the DC-8 sampling the inflow followed by UT outflow sampling. The DLR Falcon also sampled the convective outflow. The mobile radars and sounding units, as well as the LMA, all gathered data on this severe convection. Stormwide flash rates increased significantly from less than 100 flashes per minute at 0000 UTC 30 May to nearly 500 flashes per minute at 0130 UTC (Fig. 12a) as the storm became more organized and a left-moving supercell merged with the storm of interest. The estimated mean flash extent was 6–9 km. The storm occurred in a region of variable VOC mixing ratios, with concentrations higher over the eastern part of the sampling region than over the southern part of the sampling region. CO mixing ratios showed enhancements in the convective outflow region (90% values in Fig. 12b) with mixing ratios near 50 ppbv over the UT background (10% values). UT enhancements were also found for toluene, isoprene, and CH$_2$O compared to the UT background. The magnitude of enhanced CH$_3$O, H$_2$O$_2$, and HNO$_3$ in the convective outflow compared to their BL mixing ratios shows that moderate
amounts of CH$_2$O were scavenged and most of the H$_2$O$_2$ and HNO$_3$ were scavenged (Figs. 12c,d). NO$_x$ was around 0.2 ppbv in the boundary layer and more than 1000 pptv in the UT region, exhibiting substantial lightning-produced NO$_x$ in the convective outflow (Fig. 12d). On 30 May, the GV and DC-8 aircraft flew to the southern Appalachian region to sample the aged convective outflow from the 29 May storm. The convective outflow was sampled at 10–12-km altitude with CO between 110 and 130 ppbv, O$_3$ between 90 and 110 ppbv, and NO$_x$ still elevated at 1–2 ppbv.

**Strong convection case.** The 6 June 2012 Colorado storm was associated with the "Denver cyclone," where low-level flow is southeasterly on the plains east of Denver and is northwesterly to the west of Denver. The
southeasterly flow transports moisture into the area and the cyclone provides low-level convergence, which gives a focus for convective initiation. Isolated convection formed on the apex of the Denver cyclone at about 2030 UTC. As the afternoon proceeded, several convective cells formed in the DC3 network (Fig. 13). The CSU-CHILL and CSU-Pawnee radars sampled three different storms, while the DC-8 and GV sampled the inflow and outflow of two of these storm cells. The DLR Falcon also sampled convective outflow from more intense storms along the same convective line, but farther north in southeastern Wyoming. The Falcon measurements showed that in the fresh anvil outflow region, O$_3$ mixing ratios were highly variable (70–120 ppbv), indicating a pronounced mixture of O$_3$-poor air transported upward from the lower midtroposphere and at the same time downward mixing of O$_3$-rich air from the UT and lower stratosphere (LS). After 0000 UTC 7 June, the north–south-oriented line of storms intensified. Severe storms were present in the northeast Denver area as late as 0400–0500 UTC. The later storms were more intense than the sampled storms, potentially contributing substantial lightning-generated NO, flowing out of the Colorado domain. During the time when the aircraft sampled the storms, flash rates reached 400 flashes per minute and mean flash extents were around 6 km (Fig. 14a). Like the 21 May Alabama storm, the flash extent showed some anticorrelation with flash rate. VOC and CO vertical profiles show moderate enhancement in convective outflow compared to UT background air. Soluble trace gases were low in the convective outflow, indicating scavenging of these species. On 7 June, the GV and DC-8 aircraft flew to the Missouri region to sample the aged convective outflow from the 6 June
storm. The second-day convective outflow, sampled between 10- and 13-km altitude, measured moderate CO mixing ratios (95–100 ppbv) with NO\textsubscript{x} mixing ratios peaking over 1 ppbv and corresponding O\textsubscript{3} peaks of over 100 ppbv.

**Smoke ingestion case.** The 22 June 2012 Colorado thunderstorms sampled by the GV and DC-8 aircraft and ground facilities consisted of three isolated, severe storms. Although the 1200 UTC Denver temperature sounding showed a strong cap at about 1 km above ground level (750 hPa), south-southeasterly flow in eastern Colorado and western Kansas and Nebraska and high CAPE suggested the potential for strong severe convection in northeast Colorado. In addition, the High Park fire west of Ft. Collins had been burning since 9 June 2012. Before conducting storm inflow and outflow observations, the DC-8 aircraft sampled the smoke plume from this fire near its source west of Ft. Collins. At about 2100 UTC, an isolated cell formed northwest of Akron, Colorado, located about 150 km northeast of Denver. As this first storm moved eastward and dissipated, a second storm began at 2230 UTC along the Cheyenne Ridge.
Then, a third storm formed near Ft. Morgan, Colorado, at 2330 UTC. The two DC3 aircraft sampled the inflow and outflow in all three of these storms. The lightning data obtained from the two later storms showed lightning flash rates of up to 150 flashes per minute and flash extents generally of 7–15 km but up to 40 km (within the storm anvil; Fig. 16a). The flash extent again exhibited an anticorrelation with flash rate, especially for the first 2–3 h of these storms. During the same time period, the High Park fire began to burn new forest, producing a copious amount of smoke flowing northeastward. By 0000 UTC 23 June, the northern (in southwest Nebraska) thunderstorm was ingesting the High Park fire smoke plume (Fig. 15). The two aircraft observed biomass-burning signatures (e.g., high levels of black carbon, HCN, CH$_3$CN, CO, and other VOCs) in the anvil of the storm, and the DC-8 aircraft descended to sample the smoke plume just ahead of the thunderstorm at about 7-km altitude. The BL composition (Figs. 16b–d) that did not include targeted smoke plumes had approximately 1–120 ppbv CO, 1–2.5 ppbv CH$_3$O, and approximately 0.2 ppbv of NO$_x$. In the convective outflow, the aircraft sampled 100–120 ppbv CO, up to 1.5 ppbv CH$_3$O, and up to 4 ppbv NO$_x$. In contrast, the smoke plume at 7-km altitude had over 1200 ppbv CO, up to 35 ppbv CH$_3$O, and over 10 ppbv NO$_x$. The unique biomass-burning trace gases and particles can be used to understand entrainment of midtropospheric air into deep convection as well as the impact of both convection and biomass burning on UT chemistry.

**Dissipating MCS case.** To address the second DC3 goal of photochemical aging in convective outflow.
plumes, the convective outflow air mass of the 21 June 2012 decaying MCS was characterized by the GV and DC-8 aircraft. The MCS, which developed over Nebraska during the night, was located over Missouri by early morning when it began to dissipate (Fig. 17). The DC-8 aircraft flew to the convective outflow region and began traversing the storm outflow at 11 km in a southwest–northeast orientation. Using guidance from the aircraft winds, the plane progressively moved these flight legs eastward to remain approximately in the same air mass. The GV aircraft joined the DC-8 at midday repeating the last half flight leg of the DC-8 before the DC-8 returned to the operations base. The GV continued the southwest–northeast flight legs during the afternoon progressively moving them eastward. While some convection remained active in northern Oklahoma, the MCS did dissipate during the day. Initially, the trace gas and aerosol measurements on the DC-8 were typical for fresh convective outflow with low concentrations of soluble gases and particle number and high concentrations of CO and VOCs. By mid- to late morning, the photochemistry began to produce very high number concentrations of particles. Overall increases of late afternoon O₃ mixing ratios from early morning were 15–20 ppbv (Fig. 18). The spikes in O₃ seen in
Fig. 15. Visible satellite imagery at 0100 UTC 23 Jun 2012 in the northeast Colorado–southeast Wyoming region for the smoke ingestion case. The storms were moving to the east. The pink and yellow lines are the DC-8 and GV aircraft flight legs, respectively, for the 2245–0215 UTC period (the airplane symbols are located at 0215 UTC).

Fig. 18 are correlated with dips in CO, indicating that these spikes are stratospheric air. Lagrangian analysis of this case should provide quantitative insight on the contributions of NO and HO to ozone as well as the conditions conducive for the new particle formation.

*Interactions between storms, biomass burning, and stratospheric air.* In addition to the five selected cases from the GV and DC-8 measurements, five of the DLR Falcon missions stand out as exceptional storms to analyze. The 6 June 2012 case was a coordinated flight that is described above. On 30 May 2012, the DLR Falcon investigated a supercell storm over the Texas–Oklahoma border interacting with a lofted biomass-burning plume from the Whitewater–Baldy fire in New Mexico and with O-rich air from the upper troposphere–lower stratosphere (UTLS) region (~150 ppbv) into the anvil outflow region down to 9 km. NO mixing ratios in the fresh anvil outflow were on average in the range of 2–3 ppbv (peak: 8.6 ppbv). The 8 June 2012 case was selected as the only DLR Falcon case with aged convective outflow (12–24 h), indicating a strong exchange of tropospheric and stratospheric air masses in the UTLS region over Kansas the day after active convection over Colorado. At 12-km altitude, lightning-produced NO (0.5–1 ppbv) was injected into the lower stratosphere (O mixing ratios around 250 ppbv) and a stratospheric intrusion mixed down to 7 km within the aged anvil outflow (O mixing ratios around 170 ppbv). On 11 June 2012, an MCS over Missouri and Arkansas was probed by all three aircraft. A biomass-burning plume from the Little Bear fire (New Mexico), with CO mixing ratios up to 700 ppbv at 7-km altitude, was measured by the DLR Falcon as far as 800 km downwind from the fire.
As in Fig. 10, but for 22 Jun 2012 Colorado region, the DLR Falcon measurements are included, and \( \text{O}_3 \) is plotted using the bottom axis in (b). The smoke plume data are not included in the profiles.

The VOC measurements taken by the Falcon in the MCS outflow indicate that portions of the lofted biomass-burning plume were ingested into the MCS. Peak NO mixing ratios measured by the Falcon in the MCS were up to 5 ppbv (average: 2–3 ppbv). The last-selected Falcon mission was the 12 June 2012 case. The fresh outflow from a squall line over southeast Colorado and southwest Kansas was probed stepwise for a number of cruising levels between 9.5 and 12 km. Again, a pronounced interaction between the convective system, a biomass-burning plume from the High Park fire in Colorado (lofted to 7–10-km altitude), and a stratospheric intrusion (down to 8 km) was observed. At 12 km, lightning-produced NO was injected into the lower stratosphere (\( \text{O}_3 \) mixing ratios around 250 ppbv). In this case, NO mixing ratios averaged 1–2 ppbv, but reached 3 ppbv, which is slightly lower compared to the observations in the 11 June MCS and 30 May supercell case.

**SUMMARY.** In this study, we show that the DC3 field experiment successfully sampled thunderstorm inflow and outflow regions to estimate entrainment and scavenging efficiencies of trace gases and aerosols. Along with the aircraft measurements, the data collected on storm structure, kinematics, and...
lightning are providing insight into several objectives. First, by analyzing storm structure, kinematics, and lightning flash rate together, improved or new ways of predicting flash rate based on storm parameters, such as graupel volume, updraft volume, and ice flux, are being investigated. Also being considered are new parameterizations based on flash extent rather than flash rate, similar to Beirle et al. (2014) but in a more in-depth manner, as the DC3 data constitute several hours for each storm sampled. Second, by combining aircraft measurements and lightning data, new estimates of the production of NO$_x$ from lightning are being calculated for several different storms. These estimates can then be placed in context of previous field campaigns from both the midlatitudes and tropics to determine if we can reduce the uncertainty in lightning-NO$_x$ production rates and learn whether including other parameters (e.g., lightning flash extent and vertical placement, CAPE, and vertical wind shear) can improve lightning-NO$_x$ production predictions. Third, by combining storm structure and aircraft measurements, connections between cloud microphysical processes (e.g., riming) and trace-gas and aerosol scavenging can be estimated, allowing us to better predict the fate of soluble trace gases and aerosols in storms. A fourth, very interesting finding during DC3 was the effect of thunderstorm dynamics on biomass-burning plumes. In addition to the ingestion of the High Park fire biomass-burning plume into the 22 June 2012 northeast Colorado storm, other cases, primarily observed by the DLR Falcon aircraft, provide evidence of deep convective systems.
lofting biomass-burning plumes, penetrating into the lowermost stratosphere, and generating stratospheric intrusions along the sides of storms. Additional studies show that the aircraft data, especially the DC-8 lidar data, provided unique depictions of convective-induced mixing between the stratosphere and troposphere, via both direct injections of water into the stratosphere (Homeyer et al. 2014) and wrapping of stratospheric air around the anvil of storms (Pan et al. 2014). The DC3 data are also being analyzed to characterize different anthropogenic and biogenic sources of volatile organic compounds and the tropospheric distribution of aerosol composition, including brown carbon (Liu et al. 2014).

We show that the DC3 campaign successfully sampled the chemical aging of convective outflow either by sampling the storm’s outflow a day later or by measuring the convective outflow of an MCS while the storm evolved from a strong active stage to a dissipating stage. Sampling the convective outflow region of a dissipating MCS proved to be a huge success. During this 11-h time period, the DC-8 and GV observed increases of O_3 by 15–20 ppbv, nitric acid, and other trace gases produced by photochemistry, as well as new particle formation.

The analysis conducted in this study showed that the storms sampled during DC3 had high CAPE and strong vertical wind shear for the Oklahoma–Texas region and low CAPE and low vertical wind shear in the Alabama region, with Colorado storms falling between these extremes. When comparing lightning flash rates with mean flash extents, we often found that when flash rate increased, flash extent decreased and vice versa. The Colorado boundary layer had the lowest influence from biogenic VOCs, while Alabama boundary layer had the highest biogenic VOC mixing ratios. Aerosol loadings in all three regions were typical rural levels or greater. The organic aerosol was often the main PM1 constituent in the boundary layer for all three regions, although Alabama had a larger sulfate contribution than the other two regions.

The DC3 field experiment provides a unique dataset on thunderstorms, including the storm kinematics, physical structure, electrical activity, and the chemical composition of the troposphere as affected by deep convection. The archived data are publicly available at the NCAR Earth Observing Laboratory website (www.eol.ucar.edu/projects/dc3). Future papers on DC3 will report on individual case studies, syntheses of results from several case studies on specific objectives, and numerical simulations of lightning-NO_x production, convective processing of chemical constituents, and chemical aging in convective outflow regions.

ACKNOWLEDGMENTS. DC3 was a complex field campaign coordinating aircraft facilities and ground-based facilities at three different locations. There are many people to thank, each responsible for making the campaign successful. Specifically, we thank the DC-8 HDSP2 team—Rushan Gao, Joshua Schwarz, Anne Perring, John Holloway, and Milos Markovic—for the black carbon data used for the PM1 calculation. The National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Deutsches Zentrum für Luft- und Raumfahrt (DLR), and the National Oceanic and Atmospheric Administration (NOAA) are gratefully acknowledged for sponsoring the DC3 field experiment. The field project support provided by NCAR/EOL staff, especially Vidal Salazar and Jim Moore, is greatly appreciated. Data from the field campaign can be found at the NCAR/EOL field projects catalog (www.eol.ucar.edu/projects/dc3).
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— FRANKLIN W. NUTTER,
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**Living on the Real World:**
**How Thinking and Acting Like Meteorologists Will Help Save the Planet**

WILLIAM H. HOOKE

Meteorologists sift through a deluge of information to make predictions every day. Instead of being overwhelmed by the data and possibilities, they focus on small bits of information while using frequent collaboration to make decisions. With climate change a reality, William H. Hooke suggests we look to the way meteorologists operate as a model for how we can solve the twenty-first century’s most urgent environmental problems.
This monograph pays tribute to one of the leading scientists in meteorology, Dr. David Atlas. In addition to profiling the life and work of the acknowledged “Father of Radar Meteorology,” this collection highlights many of the unique contributions he made to the understanding of the forcing and organization of convective systems, observation and modeling of atmospheric turbulence and waves, and cloud microphysical properties, among many other topics. It is hoped that this text will inspire the next generation of radar meteorologists, provide an excellent resource for scientists and educators, and serve as a historical record of the gathering of scholarly contributions honoring one of the most important meteorologists of our time.
EarthCARE, a joint ESA–JAXA satellite to be launched in 2018, will provide global profiles of clouds, aerosols, and precipitation properties together with derived radiative fluxes and heating rates.

The Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) satellite is a joint mission by the European Space and Japanese Aerospace Exploration Agencies scheduled for launch in 2018. Data from its cloud profiling radar, with Doppler capability, high-spectral-resolution lidar, and multispectral imager will be used to retrieve global profiles of cloud, aerosol, and precipitation properties. Radiation fields predicted from these profiles will be compared with observations made by its broadband radiometer. These data will be used to evaluate the representation of clouds, aerosol, precipitation, and associated radiative fluxes within climate and weather forecasting models and to assess if different, more physically
based, parameterization schemes within the models can improve these representations.

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2013) states that “Climate models now include more cloud and aerosol processes, and their interactions, than at the time of AR4, but there remains low confidence in the representativity and quantification of these processes in models.” Moreover, the largest single cause of uncertainty in anthropogenic radiative forcing is from the indirect effect of aerosols on clouds; estimates range between –1.33 and –0.06 W m⁻². Figure 1 shows the range of predicted changes of cloud radiative forcing (2.5 W m⁻²) between 2006 and 2100 for eight Coupled Model Intercomparison Project (CMIP5) models each forced with the same emissions and forecasting a 3.7 ± 1 K temperature increase, whereas the direct radiative forcing from doubling CO₂ is estimated at 3.7 W m⁻². A recent white paper on “grand challenges” (Bony and Stevens 2012) emphasizes the importance of the interactions between clouds, greenhouses gases, and aerosols in a changing climate. Global numerical weather prediction models have made enormous strides over the past decade and most are expected to have a resolution of 8 km, or better, when EarthCARE is launched. The remarkable ability of the 3.5-km-gridded Nonhydrostatic Icosehedral Atmospheric Model (NICAM), with forward simulations by the Joint Simulator, to represent the Tropical Cyclone Fengsheng is displayed in Fig. 2 (Hashino et al. 2013). The close similarity between the forward-modeled and observed radar and lidar profiles indicates their potential for use in data assimilation, as has indeed been demonstrated by Janisková et al. (2012).

EarthCARE can be considered an evolution of the very successful CloudSat (Stephens et al. 2008) and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO; Winker et al. 2010), which were launched into the A-Train constellation in 2006 in a 705-km orbit. CloudSat’s 94-GHz cloud radar and Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) measure global profiles of cloud and aerosol properties. When combined with other instruments in the A-Train such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and top-of-atmosphere (TOA) fluxes inferred from Clouds and the Earth’s Radiant Energy System (CERES), they give a detailed picture of the global distributions of clouds and aerosols and how they interact with radiation and the hydrological cycle. These data have been used in many multimodel evaluations. For example, Koffi et al. (2012) analyzed the aerosol distribution in 20 global aerosol models and found they overestimated the extinction above 6-km height; Nam et al. (2012) compared eleven climate models and found that tropical boundary layer clouds were ‘too few and too bright’; Li et al. (2013) reported that the mean annual ice water path in 19 climate models varied by factors of 2–10, and Li et al. (2012) looked at 20 models and discovered regional radiation biases in annual mean fluxes of up to ±30 W m⁻². In terms of addressing model physics, the data have been used to show how replacing diagnostic ice with a prognostic scheme results in a better ice water distribution (Delanoë et al. 2011) and have identified that the “autoconversion” term in

![Fig. 1. The range of the change in cloud radiative effects predicted from 2006 to 2100 from eight different models for the same CO₂ increase and associated with global temperature rises of between 2.7 and 4.7 K depending on the model. The oscillations in the envelope show the large interannual variability. Several papers (e.g., Dufresne and Bony 2008) have shown that more than 70% of this intermodel spread on global mean temperature increase is due to uncertainty on cloud feedback.](image-url)
most models converts cloud liquid water to rain too rapidly (Suzuki et al. 2010). The data have further been used to provide the first global climatology of snowfall (Liu 2008) and light rainfall over the ocean (Berg et al. 2010) and have been used to quantify the radiative impact of subvisual cirrus (Sun et al. 2011). Zhang et al. (2010) report that over 30% of midlevel clouds have a thin layer of supercooled liquid at cloud top; these layers have a strong radiative effect but are absent in the climate models. In the next sections, we discuss how the observations from EarthCARE may help to resolve some of the model discrepancies.

THE FOUR EARTHCARE INSTRUMENTS AND SINGLE-SENSOR ALGORITHMS.
Overview. EarthCARE will carry four instruments on a single platform in a 393-km orbit. Table 1 provides a brief summary of EarthCARE’s instruments; Fig. 3 describes instrument sampling geometries and the orbit. The 355-nm high-spectral-resolution lidar (HSRL) will separate the backscatter return from

Fig. 2. Global simulation by the 3.5-km-gridded NICAM model: (top) simulated visible radiances, TOA upward longwave flux (W m$^{-2}$), and 94-GHz CPR signal (dBZ) on 18 Jun 2008. For the visible image, the cloudy-sky RGB was created with simulated MODIS 1, 4, and 3 band radiances, and the clear-sky part was filled with Blue Marble: Next Generation (http://earthobservatory.nasa.gov/Features/BlueMarble/). (bottom) Regional segments of observed and simulated brightness temperature at 10.8 µm (K) with a Tropical Cyclone Fengsheng and height-distant cross sections for CPR (dBZ) and lidar (log10 of 1 m$^{-1}$ sr$^{-1}$) signals along the CloudSat orbit (white line) on 18 Jun 2008. The observed brightness temperature was taken from Himawari.
### Table 1. The specifications of the four EarthCARE instruments and examples of the products.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Characteristics</th>
<th>Example products and synergy</th>
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<tbody>
<tr>
<td>Atmospheric lidar (ATLID) 355 nm</td>
<td>Transmits 38 mJ pulses at 51 Hz. High-spectral-resolution receiver with Rayleigh and Mie copolar and total cross-polar channels. Telescope diameter 0.62 m. Beam divergence 45 μrad, ground footprint about 30 m. Receiver field of view 65 μrad. Pointing 3° off-nadir along track to avoid specular reflection from ice crystals. Vertical-resolution 103 m from –1 to 20 km in height and 500 m from 20 to 40 km. Horizontal resolution 285 m (two shots).</td>
<td>Aerosol products: profiles of extinction, backscatter, depolarization ratio, lidar ratio (all with uncertainties), and aerosol type. Cloud products: IWC, effective radius, cloud-top height, cloud and aerosol synergy products with CPR and MSI.</td>
</tr>
<tr>
<td>Cloud profiling radar (CPR) 94.05 GHz</td>
<td>2.5-m antenna. Nadir pointing. 0.095° (3 dB) beam width; 660-m ground footprint. Extended Interaction Klystron (EIK), 3.3-μs pulses. Pulse repetition frequency 6100–7500 Hz. Doppler capability, 500-m vertical resolution, oversampled at 100 m down to 1 km below the surface. Horizontal sampling 500 m.</td>
<td>Cloud and vertical motion products. Synergy with ATLID and MSI: narrow swath profiles of liquid and ice-cloud content and extinction, particle size and concentration, and precipitation rates (all with uncertainties).</td>
</tr>
<tr>
<td>Multispectral imager (MSI)</td>
<td>Nadir pushbroom imager with seven channels: 0.670, 0.865, 1.65, 2.21, 8.80, 10.80, and 12.00 μm. To reduce sunglint the swath is tilted to right of ground track looking forward along the orbit, so it is 115 km to the right, 35 km to the left. Sampling 500 m × 500 m at nadir.</td>
<td>Cloud and aerosol products. Radiance used to construct 3D cloud–aerosol scenes around narrow swath of retrieved profiles, leading to estimates of radiative flux and heating rate profiles.</td>
</tr>
<tr>
<td>Broadband radiometer (BBR)</td>
<td>Channels: 0.25–50 μm, 0.25–4 μm; three fixed telescopes: nadir, forward, and backward (at 50° viewing zenith angles). Radiometric accuracy: SW 2.5 W m⁻² sr⁻¹; LW 1.5 W m⁻² sr⁻¹. Mean radiances averaged to 10 km × 10 km will be oversampled and reported every ~1 km along track.</td>
<td>Observed solar and thermal radiances and their derived fluxes are compared with those predicted by radiative transfer models applied to 3D constructed scenes.</td>
</tr>
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</table>

clouds and aerosols from the molecular return, thus providing a direct measurement of the extinction profile of clouds and aerosols and, when combined with the cross-polar return, better identification of aerosol type and ice particle characteristics. The EarthCARE cloud profiling radar (CPR) will have a Doppler capability and so give information on convective motions as well as ice and rain fall speeds, leading to improved drizzle, rainfall, and snowfall rates. The additional 7 dB of sensitivity (a factor of 5) compared with CloudSat will enable it to better detect thin ice clouds and much more low-level stratus and stratocumulus. The radar and lidar signals will be combined with observations from the multispectral imager (MSI) within an optimal-estimation framework to give a detailed 2D profile of the properties of the clouds and aerosol. The information from the broader swath of the MSI will be used to extend the 2D profiles into a full 3D domain; this 3D domain will be used as input to broadband radiative transfer models so that fluxes, heating rates, and radiances may be computed and TOA radiances and fluxes compared to those derived from EarthCARE’s broadband radiometer (BBR). Simulations described in this paper suggest that it will be possible to compute TOA fluxes and compare them with the BBR observations over each 10 km × 10 km scene to an accuracy of 10 W m⁻². The comparison between the modeled and observed BBR observations will provide a unique and useful consistency evaluation of the retrievals that will be used to help evaluate and improve EarthCARE products.

These data will be invaluable for studying cloud, aerosol, precipitation, and radiation processes and how they vary on a seasonal and regional scale. Comparison of the observations with climate and weather models will enable the testing of the various parameterization schemes, such as ice particle fall speed, ice particle size distributions, ice mass versus size, and autoconversion of liquid water to rain. This can be done at a statistical level by comparing climate models with observations and seeing how well the mean properties and the probability distribution functions of the cloud, aerosol, precipitation, and radiation variables, together with their geographical and seasonal changes, are captured by the models. For weather models and climate models run in forecast mode, individual scenes can be compared at 10 km × 10 km resolution. To enable EarthCARE data to be assimilated into forecast models, it is expected that nominal level 1 (L1) data will be available within
Estimating Doppler velocities from space is difficult (see related sidebar “Challenges in measuring Doppler velocity from space”) because of satellite motion, velocity folding, and nonuniform beam filling (NUBF). CloudSat is calibrated by periodically pointing the beam 11° across track and measuring the (known) sea surface return; EarthCARE CPR calibration will be slightly different, involving a periodic 10° sweep across track. In addition, as for CloudSat, the precise antenna beam pattern and radiometric performance will be evaluated by placing active radar calibrators (ARCs) within the footprint of the CPR as it overflies Japan (Horie et al. 2012). In addition to using the ARCs to validate the CPR antenna pointing, simulations (Battaglia and Kollias 2014) have shown that Doppler returns from natural targets, such as high cirrus clouds over the length of an orbit, can be used to estimate the accuracy of the pointing bias of the antenna and reduce its impact on the Doppler uncertainty.

A pulse-pair method will be used for the Doppler measurements using the phase shift between echo signals from successive pulses; however, velocity ambiguities arise when this phase shift exceeds ±180°. With a pulse repetition frequency (PRF) of 7.5 kHz (pulse separation 20 km) this leads to a folding velocity of 6 m s⁻¹. The motion of the satellite induces a 3.8 m s⁻¹ Doppler width in the target return; the lower this Doppler width is compared with the folding velocity, the more accurate is the retrieved Doppler velocity. Accordingly, the highest possible PRF is chosen compatible with the pulse separation being less than the cloud depth, and a variable PRF is adopted with range windows of 20, 16, or 12 km depending on the latitude.

An example of correction algorithms using the high-resolution observations from the 94-GHz Atmospheric Radiation Measurement Program (ARM) cloud radar during its deployment in the
Black Forest, Germany (48°32´24˝N, 8°23´49˝E), is displayed in Fig. 6. The biases introduced by the NUBF within the EarthCARE CPR footprint can be estimated (Tanelli et al. 2002; Sy et al. 2014) and are displayed in Fig. 6b. The simulated, uncorrected EarthCARE Doppler velocities at 1-km integration are shown in Fig. 6c where the noisy Doppler velocities in regions with radar reflectivities below −20 dBZ have been suppressed (Kollias et al. 2013). The NUBF biases are easy to detect near cloud edges and in areas with strong horizontal reflectivity gradients. CPR velocity folding is noticeable in liquid precipitation (e.g., at ranges between 200 and 250 km). Furthermore, the CPR velocity field is noisier than the ARM Doppler velocity field owing to the Doppler fading effect arising from satellite motion.

Figure 6d displays the results of using the 500-m integrated reflectivities simulated for the EarthCARE CPR and applies a NUBF correction [of order 0.2 m s$^{-1}$ (dBZ km)$^{-1}$ in magnitude] based on the gradient of reflectivity across the 1-km footprint. Velocity unfolding is also performed using velocity continuity in the low levels. In areas with high signal-to-noise ratio the simulated CPR velocity uncertainty is below 0.5 m s$^{-1}$. Retrievals in vigorously convective regions will be much more challenging. Further details of Doppler velocity correction techniques can be found in Schutgens (2008) and Sy et al. (2014).

The CPR cloud mask algorithm, based on Doppler cloud radar data from the Research Vessel Mirai (Okamoto et al. 2007, 2008) and CloudSat (Hagihara et al. 2010), uses signal-to-noise ratio and spatial continuity to identify clouds. Classification into cloud particle types utilizes vertical structures of reflectivity, Doppler velocity, and temperature to identify three-dimensional ice (3D), horizontally oriented ice (2D), liquid water, the melting layer, snow, and rain. Ice-scattering properties and reflectivity-weighted terminal velocity are estimated in terms of shape, orientation, and size by the discrete dipole approximation (Sato et al. 2010).
et al. 2009) to retrieve the following properties: effective radius, ice and liquid-water content, snow and rain rate and their amount, sedimentation velocity, and vertical air motion (Sato et al. 2009; Sato and Okamoto 2011).

355-nm high-spectral-resolution lidar. The EarthCARE atmospheric lidar (ATLID) is a linearly polarized HSRL (Shipley et al. 1983) transmitting a spectrally narrow laser line at 355 nm and separating the backscatter return into three channels: a “Mie” channel, receiving the copolar return from clouds and aerosols; a copolar “Rayleigh” channel, receiving copolar backscatter from atmospheric molecules; and a channel receiving the total backscattered cross-polar signal.

In the absence of any attenuating cloud or aerosol, the profile of the Rayleigh channel is defined by the known profile of air density. The extinction profile of the clouds and aerosols can be derived from the observed reduction in the Rayleigh profile below this expected value. This extinction profile may then be used to correct the observed attenuated Mie backscatter profile, and the true “lidar” or “extinction-to-backscatter” ratio ($S$) may be calculated (see “Optical depth from the HSRL” sidebar and the associated figure). In contrast, a simple elastic backscatter lidar like CALIOP must assume a value for $S$ in order to estimate the extinction coefficient (Omar et al. 2009) or, in the case of isolated layers embedded in clear air, constrained retrievals using molecular scattering below and above the layer as a reference are applied (Young and Vaughan 2009).

The nighttime copolar Mie-channel performance of ATLID should be similar to the 532-nm CALIOP channel, but better daytime sensitivity is expected because of reduced background noise due to the smaller field of view, the narrower

Fig. 4. Flowchart showing level 1, 2a, and 2b products scheduled to be in place when EarthCARE is launched. Level 2a geophysical products are derived from a single instrument’s data, while level 2b products use synergistic data from more than one instrument.

Fig. 5. The 2.5-m antenna for the 94-GHz radar.
0.3 nm filter, and the lower levels of earthshine than at 532 nm. Absolute calibration of the Rayleigh channel will be achieved by long integrations (e.g., 500 km horizontal) of the molecular returns between 35- and 40-km height. Cross-talk leakage between the Rayleigh and Mie channels will be determined by hardware-based onboard spectral calibration so that the Mie channel can be calibrated via the leaked Rayleigh signal. More details on the technical specifications of ATLID can be found in Durand et al. (2007).

Figure 7 gives an indication of the expected performance of the ATLID HSRL for retrieving aerosol extinction and backscatter profiles compared with a 532-nm CALIPSO-type retrieval. This example is based on a simulated aerosol field from the Deutscher Wetterdienst (DWD)—Consortium for Small-Scale Modeling (COSMO) model, used as input to the lidar component of the EarthCARE simulator (ECSIM) (Voors et al. 2007). The simulations include the effects of instrument noise and, for ATLID, cross talk between the Rayleigh and Mie channels. The profiles obtained by running retrieval algorithms on the simulated signals for a 50-km horizontal distance are displayed in Fig. 7, highlighting the superior performance of the HSRL technique over the backscatter lidar approach when the aerosol layer extends down to the surface. Here, the uncertainty in the CALIPSO retrieval is mainly due to the range of assumed values of $S$ used in the retrieval procedure ($65 \pm 20$ sr at 532 nm). Using the wrong value of $S$ will, in effect, lead to the wrong extinction correction being used to estimate the true backscatter profile from the observed attenuated backscatter profile. In the present case, a 30% uncertainty in $S$ leads to a 30% overcorrection of the two-way attenuation in the observed backscatter signal and a further 30% error, making 60% in total, when $S$ is used

![Fig. 6. Demonstration of the correction of CPR Doppler velocities observed from space. (a) Mean Doppler velocity observed by the ground-based 94-GHz ARM cloud radar on 9 Aug 2007 during its Black Forest, Germany, deployment. (b) Estimated Doppler velocity bias due to nonuniform beam-filling conditions within the CPR sampling volume. (c) Simulated CPR Doppler velocity at 1-km along-track integration (no correction). (d) Simulated CPR Doppler velocity at 1-km along-track integration with nonuniform beam-filling and Doppler velocity folding correction. Simulated CPR Doppler velocities at radar reflectivities below -20 dBZ are not shown (black areas).]
together with the estimated backscatter profile to calculate the total layer optical thickness. The errors in the retrieved profile due to an error in the specified value of $S$ are strongly dependent on the two-way transmission to the layer top; thus, for larger optical depths, the profile errors propagating down from the layer top can be much higher than those shown here.

Clouds, in general, lead to higher attenuated backscatter and Rayleigh-channel attenuations than is the case for aerosols. Methods using the Mie and Rayleigh channel returns together within an optimal-estimation framework are in advanced development and, apart from clouds such as tenuous cirrus, should deliver cloud products at the 1-km horizontal scale. Cloud detection will be provided at scales down to the native resolution of 143 m for one shot or 285 m for two onboard summed shots.

Liquid-water and ice partitioning is one of the major sources of uncertainties in sensitivity studies of future climate (Watanabe et al. 2010). Discrimination between cloud, aerosol, and molecules may be achieved from HSRL data after noise reduction using wavelet analysis based on the technique of Okamoto et al. (2008). Yoshida et al. (2010) demonstrated how clouds may be classified from CALIOP depolarization and the extinction estimated using a forward-modeling technique that includes multiple scattering and physical optics (Okamoto et al. 2010).

The quantification of direct aerosol radiative forcing in general and the achievement of radiative
Fig. 7. Retrieval of backscatter and extinction profiles using simulated ATLID HSRL signals at 355 nm (blue) compared with the profiles retrieved with corresponding simulated CALIOP signals at 532 nm (green). A simulated sulfate aerosol field was used with an effective radius of 0.5 µm so that the aerosol optical depth is 0.233 at 355 nm with the lidar ratio ($S$) equal to 35 sr, and 0.254 at 532 nm with $S = 65$ sr. ECSIM was used to simulate the signals corresponding to a 50-km horizontal integration for the ATLID Rayleigh and Mie channels and the 532-nm channel of CALIOP. The lines are obtained by running corresponding HSRL and 532-nm backscatter retrieval algorithms on the simulated lidar signals. The black lines are the “true” profiles; the blue and green lines are the retrieved profiles. The spread in the green (532 nm) retrievals is due to the choice of $S$ from 45 to 85 sr while the error bars show the smaller uncertainty due to random noise effects. Note that the HSRL errors for the inferred layer optical thickness and integrated backscatter (IB) are 8% and 7%, respectively, but for the backscatter lidar they are 64% and 42%.
and the cold-space viewport. Radiometric performance in the visible and near-infrared channels is specified as a signal-to-noise ratio of about 70 for dim scenes and 500 for bright scenes, and about 20 and 250, respectively, for these scenes in the shortwave infrared. Noise requirement for the TIR channels is 0.80 K for cold (220 K) and 0.25 K for warm (293 K) scenes. Long-term radiometric stability over one year is anticipated to be better than 1% for solar channels and 0.3 K for TIR channels.

MSI data will be used to 1) infer column-integrated aerosol and cloud properties, 2) constrain synergistic retrievals, and 3) construct small 3D atmospheres around the 2D cross section retrieved from the radar and lidar. In the first step of the data analysis, cloud-screening algorithms establish each pixel as cloudy or clear and determine the cloud thermodynamic phase by applying static and dynamic threshold tests to radiances (Ishida and Nakajima 2009). In the second step, all MSI pixels are analyzed to retrieve aerosol optical depth, aerosol Ångström exponent, cloud optical depth, effective particle radius, cloud-top temperature, and pressure. Aerosol optical depth is retrieved at 0.6 \( \mu \)m over ocean and land as well as at 0.8 \( \mu \)m over ocean (Higurashi et al. 2000; von Hoyningen-Huene et al. 2003). Cloud microphysical retrievals are based on the combination of visible channels (0.6 \( \mu \)m, 0.8 \( \mu \)m) and near-infrared channels (1.6 \( \mu \)m, 2.2 \( \mu \)m). Cloud-top height retrieval is limited to infrared-window channels, but an improved estimate along the lidar track can be obtained via synergy with ATLID. Additionally synergistic analysis using CPR, ATLID, and MSI measurements have been developed using data from CloudSat, CALIOP, and MODIS (e.g., Nakajima et al. 2010; Suzuki et al. 2010).

**Multiangle broadband radiometer.** The BBR will measure TOA reflected solar and emitted thermal radiances in three viewing directions (Fig. 3, Table 1) with a time delay of \(~150\) s between forward and backward views of a surface target. The swath is sufficiently wide so that the three views align along the satellite track, yielding excellent characterizations of the surface-atmosphere anisotropy. The BBR telescopes measure total-wave radiances from 0.25 \( \mu \)m to beyond 50 \( \mu \)m. Applying an uncoated synthetic quartz filter

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**Fig. 8.** Aerosol classification from measurements of lidar ratio and particle linear depolarization ratio at 355 nm. Ground-based observations were performed with the Raman-polarization lidars (POLIS) (University of Munich, dots) and PollyXT (Leibniz Institute for Tropospheric Research, open squares) at Cape Verde (dust, marine, dust and smoke, dusty mixtures; dots; Groß et al. 2011); Leipzig, Germany (pollution, aged boreal biomass-burning aerosol, dusty mixtures; open squares); Munich, Germany (volcanic ash; dots; Groß et al. 2012); and over the North Atlantic (dust, dust and smoke; open squares; Kanitz et al. 2013).
mounted on a rotating drum to each telescope results in the shortwave (SW) channel covering 0.25–4.0 µm. Longwave (LW) radiances are obtained by differencing the two channels. To remove instrumental spectral response effects, measured radiances are “unfiltered,” thus isolating estimates of actual SW and LW radiances (Velázquez-Blázquez and Clerbaux 2010). Radiometric calibration will be performed using on-board hot and cold black bodies. Aging effects on the SW channel will be monitored with a solar calibration board hot and cold black bodies. Aging effects on the LW radiances (Clerbaux et al. 2003; Domenech et al. 2011). Anisotropic factors were estimated through multiple regressions on simulated MSI brightness temperatures and corresponding LW fluxes (Clerbaux et al. 2003; Domenech and Wehr 2011) and assessed via comparison to CERES ADMs (Loeb et al. 2005). Inputs are BBR SW radiance, angular geometry, weighted MSI radiances surface descriptors, and cloud fraction inferred from MSI. LW ADMs are based on correlations between the anisotropy of BBR radiances and spectral information provided by MSI LW radiances (Clerbaux et al. 2003; Domenech et al. 2011). Anisotropic factors were estimated through multiple regressions on simulated MSI brightness temperatures and corresponding LW fluxes computed by a 1D radiative transfer model.

**SYNERGY ALGORITHMS.** A notable successful application of sensor synergy is provided by the development and deployment of combined lidar and cloud radar algorithms for the retrieval of cloud macro- and microphysics (e.g., Donovan et al. 2001). Lidars are sensitive to small cloud/aerosol particles, but lidar signals can often be strongly attenuated by clouds. Cloud profiling radars are not strongly attenuated by clouds but are not sensitive to small cloud particles and can miss some low-level water clouds and optically thin cirrus. The combination of lidar and radar not only provides a much more complete height-resolved detection of the presence of clouds but can also provide quantitative information on the cloud particle size and water content by exploiting the different response to particle size between the two wavelengths (Okamoto et al. 2003, 2010). The lidar and radar synergy within EarthCARE also incorporates the data streams from the MSI in order both to improve the cloud and aerosol profile retrievals (e.g., Delanoë and Hogan 2010) and to provide a 2D horizontal context to the retrieved nadir profiles (Barker et al. 2011). The data processing chain of EarthCARE is being designed with sensor synergy as a guiding principle from the ground up. This will enable effective use of the total EarthCARE instrument package. In the remainder of this section we present some illustrative examples of the types of synergistic algorithm that will be employed in the EarthCARE processing scheme.

**Target classification.** Before microphysical retrieval algorithms can be applied, it is necessary to report the lidar and radar data on a common joint standard grid and to apply cloud/aerosol mask schemes (Hagihara et al. 2010) that identify particle types present at each point in the grid (Yoshida et al. 2010; Nishizawa et al. 2008). The possible radar targets are liquid-cloud droplets, ice particles, raindrops, aerosols, insects, and stratospheric particles (which may be aerosols or clouds). Combinations are possible (e.g., in mixed-phase clouds where supercooled liquid droplets coexist with ice particles). This approach builds on work to combine radar-only and lidar-only cloud masks (e.g., Hagihara et al. 2010).

Illingworth et al. (2007) made extensive use of target classification in the “CloudNET” processing of ground-based radar and lidar data, and this approach has since been applied to CloudSat and CALIPSO (Delanoë and Hogan 2010; Ceccaldi et al. 2013). The classification to be applied to EarthCARE borrows heavily from this work. Essentially, when the radar observes a signal it is interpreted as ice if above the melting layer (determined from the wet-bulb temperature in the model and the radar Doppler velocity) and rain if below. Relatively strong lidar echoes are interpreted as liquid clouds, while weaker ones are interpreted as aerosols, thin ice clouds, or stratospheric particles, depending on their height. Supercooled water can be distinguished from ice using a combination of lidar backscatter and depolarization (Yoshida et al. 2010).

**Synergistic cloud, aerosol, and precipitation retrievals.** EarthCARE will deploy two synergistic algorithms for cloud microphysics. The first builds on the ice-cloud retrievals of Okamoto et al. (2010) and Sato and Okamoto (2011) that have been applied to CloudSat and CALIOP using optimal-estimation theory to provide a rigorous estimate of retrieval uncertainties. The basic structure of the earlier version of the synergy algorithms (Okamoto et al. 2003) was adopted in the operational CloudSat and
CALIPSO synergy algorithm to produce the CloudSat 2C-ICE standard product (Deng et al. 2010). The algorithm will utilize all radar and lidar variables to reliably retrieve water content and effective radius of liquid and ice clouds, rain, and snowfall rate, as well as information on the concentration of planar ice particles. The technique of Sato et al. (2009) will be used to split the measured Doppler velocity into air motion and terminal fall-speed components.

A second “unified” algorithm, CAPTIVATE, combines the radar, lidar, and also the imager to retrieve the microphysical properties of cloud, aerosol, and precipitation simultaneously. Frequently, multiple particle types are present in the profile (e.g., liquid cloud beneath ice cloud), and CAPTIVATE is unique in being able to exploit solar radiances in this situation, which are dependent on the optical depth of all particles in the profile. Each profile is processed in turn, and the first step is to use the target classification to decide what “state variables” to retrieve that describe the properties of the particles at each vertical level. These are then used in a “forward model” that simulates the radar, lidar, and imager observations. Radar and lidar multiple scattering is accounted for using the models described by Hogan (2008). Optimal-estimation theory is used. A “cost function” is defined that penalizes differences between the observations and the corresponding forward-modeled values and between the state variables and their a priori estimates. The CAPTIVATE algorithm then finds the set of state variables that minimizes the cost function.

The ice-cloud/snow component of the CAPTIVATE algorithm inherits directly from the CloudSat–CALIOP–MODIS algorithm of Delanoë and Hogan (2010) but exploits the additional Doppler information. The liquid-cloud component retrieves liquid-water content at each height, with a “gradient constraint” added to the cost function to prevent a superadiabatic increase with height and a constraint on the total amount of liquid in the column available from the radar path-integrated attenuation (PIA) over the ocean (e.g., Lebsock et al. 2011). The rain component automatically makes use of the gradient of radar reflectivity with height to infer rain rate (Matrosov 2007) and over the ocean will also use the PIA (L’Ecuyer and Stephens 2002). An ambiguity can arise at 94 GHz when a reflectivity profile with values reducing toward the ground can be caused either by evaporating drizzle or by heavier rain attenuating the signal. In simulations, however, we have found that this can be resolved because the Doppler velocity would differ by around 2 m s⁻¹. More accurate snowfall rates can be derived using the Doppler velocity to infer the degree of riming. The aerosol component uses the HSRL molecular return to estimate the extinction profile but with a smoothness constraint in height and a Kalman smoother horizontally to cope with the noisiness of the signal. The expected effective horizontal resolution of the aerosol retrieval is 10–50 km, depending on the optical depth.

The performance of the A-Train version of CAPTIVATE is illustrated in Fig. 9, which also includes a simulation of what the EarthCARE radar and lidar would measure for the same scene. The CloudSat and CALIOP signals are shown in Figs. 9a and 9b, with the target classification information from Ceccaldi et al. (2013) in Fig. 9c. These observations have been used in a retrieval of ice, liquid cloud, rain, and aerosols. The 0.5-μm extinction coefficient of all four components combined is shown in Fig. 9d, along with its retrieval uncertainty in Fig. 9e. CAPTIVATE reports retrieval uncertainties in ice extinction of 10%–20% in the lidar–radar overlap regions but closer to 50% in the radar-only regions largely because of uncertainties in the ice-scattering model (Hogan and Westbrook 2014).

These CAPTIVATE retrievals have then been used to forward model what EarthCARE would see. First, Fig. 9f depicts the EarthCARE radar reflectivity factor, and we can see immediately the effect of the 7-dB extra sensitivity. A large fraction of the high ice cloud seen only by CALIOP would be detected by the EarthCARE radar. In this case, for clouds above 10 km (colder than −30°C), CloudSat detected 66% of the clouds seen by the lidar and EarthCARE 97%, but these figures are dependent on ice-scattering assumptions used to predict Z in the lidar-only regions. Experience with CALIPSO is that lidar-only retrievals of cirrus optical depth are less accurate when the cloud is so thick that no below-cloud molecular signal is detected. While this will also be the case for EarthCARE, the effect is mitigated by 1) the shorter wavelength leading to a much stronger molecular signal and 2) the higher radar sensitivity meaning that cirrus thick enough to obscure the lidar molecular signal will invariably also be detectable to radar. Delanoë and Hogan (2010) have demonstrated that synergy algorithms exploiting the radar return and the cloud and molecular returns from the lidar can retrieve optical depth seamlessly and reliably in such situations.

Doppler velocity is a key new EarthCARE variable. The vertical wind is not known from the A-Train alone, so we can only simulate the Doppler velocity owing to fall speeds, and this is shown in Fig. 9h using the Doppler multiple-scattering simulator of Battaglia...
and Tanelli (2011) and the corrections discussed in the context of Fig. 6d. For a 5-km integration length we expect errors to be about 0.5 m s\(^{-1}\) in regions that are not highly convective. Finally, the signals that would be measured by the Mie and Rayleigh channels of the EarthCARE lidar are shown in Figs. 9g and 9i, respectively. These were simulated using the lidar component of ECSIM and include a rigorous Monte Carlo treatment of lidar multiple scattering as well as the effects of cross talk between channels and their simulated correction.

Figure 10 illustrates the CAPTIVATE algorithm for a single data profile from Fig. 9 containing rain and ice cloud (where the latter includes snow). The top two panels confirm that at the final iteration of the algorithm, the forward model very closely reproduces the observations. The importance of incorporating the effects of multiple scattering is highlighted by the fact that when multiple scattering is omitted from the forward model (red dashed lines), the radar and lidar signals are both underestimated. Figure 9c depicts the retrieved particle size, with retrieval uncertainty, and it can be seen that the uncertainty is smallest between 12 and 15 km where both the radar and lidar receive a good signal. Figure 9d shows that the surface rain rate for this profile was around 5 mm h\(^{-1}\), and it is encouraging that precipitation flux is approximately conserved across the melting layer. Note that the strong surface return in Fig. 9a does not contaminate the rain-rate retrieval.

**Radiation and closure assessment.** Three broadband 1D radiative transfer models—CERES (Fu and Liou 1992),
Canadian Centre for Climate Modelling and Analysis (CCCma) (von Salzen et al. 2013), and the Rapid Radiative Transfer Model (Clough et al. 2005)—are each used to compute SW and LW fluxes and heating rate profiles for each retrieved column of width about 1 km. These models are widely used in the GCM and NWP community. A small 3D atmosphere (on the order of ten to a few tens of square kilometers) is constructed around the retrieved cross section (Barker et al. 2011) by comparing the MSI radiances for an off-nadir (recipient) pixel to corresponding nearby values along the nadir. Column properties of the nadir pixel whose MSI values best resemble those of the recipient are replicated at the recipient. This yields 3D domains of about 15-km perpendicular distance to the orbit track. Figure 11 shows a schematic of the scene construction process. Figure 12 displays MODIS images and their reconstructed counterparts in addition to broadband radiances computed by the 3D LW model for a small portion of the constructed domain. A-Train data used here preceded those used in Fig. 9 by ~12 h and were ~1,000 km to the west. Broadband Monte Carlo parallelized 3D radiative transfer models (Barker et al. 2012) can then be employed to provide rapid yet accurate computation of radiances and fluxes on the joint standard grid as an operational product. Uncertainties are estimated by stochastically varying the reconstructed 3D atmosphere.

Once uncertainties for computed quantities, measured radiances, and ADM-derived broadband TOA fluxes are available, one may ask what is the probability $f_{\Delta F^*}$ that simulated and ADM-derived TOA fluxes, when averaged to ~100-km$^2$ assessment domains, differ by less than $\Delta F^*$? This represents the

Fig. 10. Demonstration of the CAPTIVATE synergistic retrieval for a profile from Fig. 9 at a horizontal distance of 400 km. (a),(b) The A-Train observations in blue and the corresponding forward-modeled values at the final iteration of the algorithm in red. The forward-modeled values omitting multiple scattering are shown by the red dashed lines. (c),(d) Retrieved properties of ice-cloud/snow (green) and rain (magenta) and their one-standard-deviation uncertainties.
essence of EarthCARE radiative closure assessment. Nominally, if \( f_{\Delta F^*} \geq 0.5 \) at \( \Delta F^* \approx 10 \text{ W m}^{-2} \) for a domain containing aerosol or cloud, most would likely conclude that EarthCARE’s goal was achieved. Closure assessment is demonstrated best with end-to-end simulations, using the full representative L2 retrieval chain, but we are unable to do those as yet. Hence, results are shown in Fig. 12 for a mock assessment using the A-Train data mentioned above. A control case using the 3D scene constructed from A-Train retrievals represents flux estimates derived from BBR radiances. Uncertainty of ±5% of TOA flux was used to represent errors due to ADMs (Kato and Loeb 2005). The experiment used 15 random perturbations of the same scene to affect input uncertainties in the form of unbiased and uncorrelated Gaussian noise (relative standard deviations of ∼30% at the bases of deep clouds and decreasing with altitude) added to profiles of cloud water content and particle size. Figure 12 shows that for this best case (unbiased retrievals) ∼90% of the 100-km² assessment domains have uncertainties <10 W m⁻². Once realistic retrieval uncertainties and other atmospheric and surface uncertainties are included, success rates will decrease but are nevertheless expected to exceed ∼75%.

**VERIFICATION AND VALIDATION.** Verification and validation of EarthCARE products requires correlative observations of cloud, aerosol, precipitation, and radiation properties. The validation plan is to identify requirements, activities, and scientific teams for 1) validation by long-term ground-based observation networks, 2) satellite-to-satellite intercomparisons, and 3) field campaigns. Data from global or regional networks of ground-based systems, such as Aerosol Robotic Network (AERONET) and SKYNET radiometer networks (Holben et al. 1998; Nakajima et al. 2007), or the European Aerosol Research Lidar Network (EARLINET) and Micro-Pulse Lidar Network (MPLNET) (Pappalardo et al. 2010; Welton et al. 2001), can be used to validate EarthCARE products through statistical approaches as was done for CloudSat (Protat et al. 2010) and CALIPSO (Pappalardo et al. 2010; Omar et al. 2013). The intercomparisons with satellites—such as CloudSat, CALIPSO, Aqua, Terra, National Polar-Orbiting Operational Environmental Satellite System Preparatory Project (NPP), Geostationary Earth Radiation Budget (GERB), Global Change Observation Mission-Water (GCOM-W), and Global Change Observation Mission-Climate (GCOM-C)—will be an important contribution to complement ground-based observations in remote areas. The satellite-to-satellite validation will be worth exploiting once there are enough individual coincidences available. Field campaigns with mobile ground-based instruments and airborne systems are a very important part of the validation strategy, in particular for clouds with their small spatial structures and short temporal correlations. Cloud validation will be specifically addressed by mobile radars, such as the National Institute of Information and Communication Technology’s (NICT) new ground-based 94-GHz Doppler radar that was developed from the prototype.
Fig. 12. An example of the procedure for assessing radiative closure using A-train data starting at (15.00°S, 123.23°E; 0536:36 UTC) and ending at (10.00°N, 117.86°E; 0543:48 UTC) on 2 Jan 2007. (a) Actual and reconstructed 21-km-wide MODIS images (11.03 and 0.645 µm). Arrow indicates satellite tracking directions. (top) Broadband radiances, coregistered at altitude 15 km, simulated by a 3D LW Monte Carlo model acting on the constructed 3D domain. Off-nadir views were scaled along track by cos(55°), and unlike MODIS images, these have proper aspect ratios. (b) CloudSat–CALIPSO–CERES (C3M) cloud mask (white = ice; gray = liquid). (c) Mean visible cloud optical depth for assessment domains measuring (11 km)² centered on the CloudSat–CALIPSO cross section. (d) Difference ΔF in assessment domain mean TOA flux as computed by a 3D SW Monte Carlo algorithm applied to control and experimental atmospheres as described in the text. Here, ~4.5 × 10⁸ photons were injected over the full frame (comparable to that expected for EarthCARE) so Monte Carlo noise was negligible; fΔF*, the probability that ΔF < ΔF* for ΔF* equal to 5 and 10 W m⁻² assuming that uncertainties for TOA fluxes follow Gaussian distributions.
EarthCARE CPR. Aircraft operating remote sensing instrumentation similar to the EarthCARE payload will underfly the EarthCARE satellite to verify microphysical retrievals. Correlative observations from ground-based sites, aircraft, and other satellites will be identified over the coming years and their readiness will be reviewed at a Joint European Space Agency (ESA)–Japan Aerospace Exploration Agency (JAXA) Validation Workshop prior to launch.

**CHALLENGE AND SUMMARY.** The IPCC (2013) has reiterated our low confidence in the ability to model cloud, aerosol, and precipitation processes. EarthCARE’s Doppler cloud profiling radar and high-spectral-resolution lidar are challenging instruments to be deployed in space. By careful design and with opportunities for synergistic retrievals, the mission promises to revolutionize our ability both to understand cloud, aerosol, and precipitation processes and their response to different atmospheric processes, while simultaneously evaluating and improving models. In the introduction, we gave examples of the shortcomings of current models in representing vertical profiles of aerosol, boundary layer cloud occurrence, mean ice water path, regional radiation biases, and the radiative impact of subvisual cirrus and midlevel thin supercooled cloud layers. Below we anticipate how EarthCARE should help to resolve these issues:

1. The HSRL can provide absolute and accurate measurements of extinction coefficient and lidar ratio. For example, it should estimate an aerosol layer of optical depth of 0.2 with an accuracy of 7% over a 50-km horizontal resolution. Improved extinction profiles should lead to much better consistency between cloud/aerosol retrievals and broadband radiation measurements. Though ATLID’s wavelength is different from CALIPSO’s it is anticipated that EarthCARE will extend and refine the valuable record of global lidar aerosol measurements begun by CALIPSO.

2. A sophisticated aerosol classification allowing for a quantification of absorbing and nonabsorbing, natural, and manmade particle types will be possible using the lidar and depolarization ratios observed with the HSRL and size information from the MSI. Accurate estimates of the anthropogenic versus the natural radiative impact of aerosols on the global and the regional scales will thus be feasible.

3. With 7 dB more sensitivity than CloudSat, we expect the CPR will detect substantially more thin cirrus and stratocumulus than is currently possible.

4. The CAPTIVATE synergistic retrievals using the CPR, HSRL, and MSI should yield accurate profiles of ice content, rain rates, particle size, and extinction with quantified uncertainties. For example, in ice clouds detected by the radar and lidar, we expect extinction and ice-water-content uncertainties of only 10%–20%. There will be more occasions when clouds are detected by both the lidar and radar so that, using the MSI and the optimal-estimation approach, much improved 3D scenes can be retrieved.

5. TOA fluxes predicted to within 10 W m⁻² from these 3D scenes of size 10 km × 10 km can be compared with these values observed by the broadband radiometer and those analyzed in forecast models and climate models. This should help resolve problems such as the “too few, too bright” low tropical cloud problem and the reported regional and seasonal biases of up to ±30 W m⁻² in model TOA fluxes.

6. The more sensitive radar combined with the Doppler capability should yield more accurate snowfall and rainfall seasonal and regional climatologies, together with better characterization of drizzle production in warm clouds, ice crystal fluxes from thin supercooled layer clouds, and the degree of riming in ice clouds.

7. Doppler velocity estimates in stratiform regions should be within 0.5 m s⁻¹ for 5 km along track, thus providing information on terminal velocities of ice particles, drizzle, rain, and snow and insights into drizzle production and riming. Longer averaging will provide ice fall speed of sufficient accuracy to provide a very useful constraint for global models, in which the radiation budget has been found to be very sensitive to the fall speed prescribed (Jakob 2002).

8. The Doppler capability should extend the knowledge (Luo et al. 2010) gained from CloudSat on convective motions and entrainment processes.

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THE COMMUNITY EARTH SYSTEM MODEL (CESM) LARGE ENSEMBLE PROJECT
A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability


By simulating climate trajectories over the period 1920–2100 multiple times with small atmospheric initialization differences, but using the same model and external forcing, this community project provides a comprehensive resource for studying climate change in the presence of internal climate variability.

Internal climate variability, by which we mean unforced climate variability intrinsic to a given climate state, arises from atmospheric, oceanic, land, and cryospheric processes and their coupled interactions. Internal climate variability is known to have important effects on climate change projections, especially at regional spatial scales and subdecadal time scales (e.g., Hawkins and Sutton 2009; Deser et al. 2014). Nevertheless, internal climate variability is often underappreciated and confused with model error [e.g., as discussed in Tebaldi et al. (2011)]. Why? In general, modeling centers contribute a small number of realizations to international climate change projection assessments [e.g., phase 5 of the Coupled Model...
Intercomparison Project (CMIP5; Taylor et al. 2012)]. As a result, model error and internal climate variability are difficult, and at times impossible, to disentangle. In response, we designed the Community Earth System Model Large Ensemble (CESM-LE) with the explicit goal of enabling assessment of recent past and near-future climate change (1920–2100) in the presence of internal climate variability (Table 1). Two companion, 1000+ yr-long, preindustrial, control simulations (fully coupled, prognostic atmosphere and land only) enable assessment of internal climate variability in the absence of climate change.

Unlike perturbed physics ensembles (e.g., Murphy et al. 2004) or multimodel ensembles of opportunity (e.g., CMIP5), all 30 CESM-LE members use the same model and the same external forcing. Each CESM-LE ensemble member has a unique climate trajectory because of small round-off level differences in their atmospheric initial conditions. Simply put, the CESM-LE ensemble spread results from internally generated climate variability alone.

The influence of small, initial condition differences on climate projections in the CESM-LE parallels initial condition impacts on weather forecasts (Lorenz 1963). After initial condition memory is lost, which occurs within weeks in the atmosphere, each ensemble member evolves chaotically, affected by atmospheric circulation fluctuations characteristic of a random, stochastic process (e.g., Lorenz 1963; Deser et al. 2012b). As we will show, internal climate variability has a substantial influence on climate trajectories, an influence that merits further investigation, comparison with available observations, and communication. Evaluating the realism of internal climate variability simulated by the CESM-LE is challenging, especially on decadal time scales, but vital (e.g., Goddard et al. 2013), especially given differences in model variability (e.g., Knutson et al. 2013). Model biases can degrade the realism of simulated internal variability and forced climate responses and we therefore encourage users of the CESM-LE to understand relevant model biases and their potential ramifications.

The CESM-LE builds upon previous large ensemble projects (e.g., Roeckner et al. 2003; Deser et al. 2012b; Mudryk et al. 2014; Fischer et al. 2013) with its (i) comprehensive, community-selected, freely available, and easily accessed outputs; (ii) well-documented experimental design that enables future contributions of additional ensemble members and off-shoot experiments; (iii) simulation length from the early twentieth century to the late twenty-first century; and (iv) long (1000+ yr) companion preindustrial control simulations. Given these attributes, the CESM-LE experiment uniquely enables a diverse community to assess the influence of internal climate variability and forced climate change on the climate system.

The purpose of this article is two-fold. First, we document the CESM-LE experimental design, including model version, control run and ensemble generation, external forcing, and outputs saved. Second, we provide thought-provoking examples and promising directions for use of the CESM-LE by climate scientists and stakeholders.

**EXPERIMENTAL DESIGN.** All CESM-LE simulations use a single CMIP5 coupled climate model: the Community Earth System Model, version 1, with the Community Atmosphere Model, version 5 [CESM1(CAM5); Hurrell et al. 2013] at approximately 1° horizontal resolution in all model components. Like most state-of-the-art global coupled climate models, CESM1(CAM5) consists of coupled atmosphere, ocean, land, and sea ice component models (Fig. 1). In addition to land carbon cycle calculations, the CESM-LE simulations also include diagnostic biogeochemistry calculations for the ocean ecosystem and the atmospheric carbon dioxide cycle (Lawrence et al. 2012; Long et al. 2013; Moore et al. 2013; Lindsay et al. 2014). Unlike the land carbon cycle calculations, which affect local energy and water cycles, the ocean biogeochemistry and atmospheric carbon dioxide tracer calculations do not affect the climate of the CESM-LE simulations. Many aspects of fully coupled simulations performed with CESM1(CAM5) are documented in a special collection of the *Journal of Climate* (see [http://journals.ametsoc.org/page/CCSM4/CESM1](http://journals.ametsoc.org/page/CCSM4/CESM1)).

We began the CESM-LE with a multicentury 1850 control simulation with constant preindustrial forcing (Table 1; Fig. 2). While the ocean model was initialized from observations, the atmosphere, land, and sea ice models were initialized using previous CESM1(CAM5) simulations. Atmosphere, land, and sea ice processes have memory on short time scales (weeks to years), so the influence of their initial conditions on the coupled climate state in a multicentury-long control simulation is negligible. In contrast, the ocean has memory on long time scales (up to several thousand years in the abyssal ocean). As a result, ocean initial conditions can influence multicentury coupled climate model runs. Because global ocean observations are not available for 1850, we initialized the ocean from a state of rest (Danabasoglu et al. 2012) using modern observations. Specifically, we initialized the ocean model with January mean climatological Polar Science Center Hydrographic Climatology (PHC2)
Table 1. CESM-LE simulations. Additional information about the simulations including all of the saved variables, diagnostics, model support, and known issues can be found at the CESM-LE web page (www2.cesm.ucar.edu/models/experiments/LENS).

<table>
<thead>
<tr>
<th>Case name</th>
<th>1850 fully coupled control</th>
<th>1850 atmosphere and land control</th>
<th>Ensemble member 1</th>
<th>Ensemble member 2–N</th>
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<td>f.e1.l.F1850C5CN.f09_f09.001</td>
<td>b.e1.l. B20TRC5CNBDRD. f09_g16.001, b.e1.l. BRCP85C5CNBDRD. f09_g16.001</td>
<td>b.e1.l. B20TRC5CNBDRD. f09_g16.00N, b.e1.l. BRCP85C5CNBDRD. f09_g16.00N</td>
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<tr>
<th>Years</th>
<th>Prognostic model components</th>
<th>Forcing</th>
<th>Initialization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,500 years, years 400–1500 released</td>
<td>Atmosphere, ocean, land, sea ice</td>
<td>Preindustrial (1850), Whole Atmosphere Community Climate Model (WACCM) ozone forcing</td>
<td>Jan mean present-day potential temperature and salinity from PHC2 dataset for ocean, previous CESM1(CAM5) 1850 control run for atmosphere, land, and sea ice</td>
</tr>
<tr>
<td>2,000 years, years 1–1999 released</td>
<td>Atmosphere, land</td>
<td>Preindustrial (1850) with prescribed monthly mean sea surface temperature and sea ice averaged over years 402–1510 of the 1850 control, WACCM ozone forcing</td>
<td>1 Jan, year 402 of 1850 coupled control for atmosphere and land. For ocean/ice, N/A.</td>
</tr>
<tr>
<td>1850–2100</td>
<td>Atmosphere, ocean, land, sea ice</td>
<td>1850–2005 historical, 2006–2100 RCP8.5 well-mixed greenhouse gases (Meinshausen et al. 2011) and short-lived gases and aerosols (Lamarque et al. 2011), WACCM ozone forcing</td>
<td>1 Jan, year 402 of 1850 coupled control for all model components (atmosphere, land, ocean, sea ice)</td>
</tr>
<tr>
<td>1920–2100</td>
<td>Atmosphere, ocean, land, sea ice</td>
<td>Same as ensemble member 1 for overlapping years</td>
<td>Ensemble member 2: 1 Jan 1920 of ensemble member 1 started with 1-day lagged ocean temperatures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ensemble members 3–N: 1 Jan 1920 of ensemble member 1 for all model components; atmosphere with round-off (order of $10^{-14}$ K) differences in air temperature</td>
</tr>
</tbody>
</table>

a Simulation output using the case names listed in this table are available to download from the ESG (www.earthsystemgrid.org).

b Simulations may be extended and additional years will be posted on the ESG.

c We elected to use ozone concentrations produced by CESM1(WACCM) for the CESM-LE because the CMIP5 CESM ozone forcing underestimates the strength of stratospheric ozone depletion over Antarctica (Eyring et al. 2013). Indeed, the ozone hole is more pronounced, realistic, and internally consistent in CESM1(WACCM) than it is in the CESM CMIP5 simulations. The CESM-LE 1850 control run was forced by the average seasonal cycle of ozone concentrations from 200 years of a CESM1(WACCM) 1850 control run. For the transient ensemble members, WACCM ozone concentrations were taken from available CESM1(WACCM) CMIP5 simulations (average of two ensemble members for 1955–2055, single ensemble member for 1850–1954 and 2056–2100). Following CMIP5 external forcing protocol, we wanted the applied WACCM ozone forcing to emphasize externally forced ozone variations and deemphasize internal climate variability in the CESM1(WACCM) CMIP5 simulations. As such, we applied a 10-yr running mean to each month of ozone forcing separately. This smoothing reduces the impact of CESM1(WACCM)-specific internal climate variability (e.g., ENSO variability and sudden stratospheric warmings) on the ozone concentrations that are applied to the CESM-LE. The smoothing also minimizes the impact of the 11-yr solar cycle on stratospheric ozone concentrations.
<table>
<thead>
<tr>
<th>Model name</th>
<th>Model expansion</th>
</tr>
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<tbody>
<tr>
<td>ACCESS1.0</td>
<td>Australian Community Climate and Earth-System Simulator, version 1.0</td>
</tr>
<tr>
<td>ACCESS1.3</td>
<td>Australian Community Climate and Earth-System Simulator, version 1.3</td>
</tr>
<tr>
<td>BCC_CSM1.1</td>
<td>Beijing Climate Center, Climate System Model, version 1.1</td>
</tr>
<tr>
<td>BCC_CSM1.1(m)</td>
<td>Beijing Climate Center, Climate System Model, version 1.1 (moderate resolution)</td>
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<tr>
<td>BNU-ESM</td>
<td>Beijing Normal University–Earth System Model</td>
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<tr>
<td>CanESM2</td>
<td>Second Generation Canadian Earth System Model</td>
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<tr>
<td>CCSM4</td>
<td>Community Climate System Model, version 4</td>
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<td>CESM1(BGC)</td>
<td>Community Earth System Model, version 1 (biogeochemical)</td>
</tr>
<tr>
<td>CESM1(CAM5)</td>
<td>Community Earth System Model, version 1 (Community Atmosphere Model, version 5)</td>
</tr>
<tr>
<td>CESM1(WACCM)</td>
<td>Community Earth System Model, version 1 (Whole Atmosphere Community Climate Model)</td>
</tr>
<tr>
<td>CMCC-CMS</td>
<td>Centro Euro-Mediterraneo per I Cambiamenti Climatici Stratosphere-resolving Climate Model</td>
</tr>
<tr>
<td>CNRM-CM5</td>
<td>Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5</td>
</tr>
<tr>
<td>CSIRO-Mk3.6.0</td>
<td>Commonwealth Scientific and Industrial Research Organisation Mark 3.6.0</td>
</tr>
<tr>
<td>EC-EARTH</td>
<td>European Consortium Earth System Model</td>
</tr>
<tr>
<td>FGOALS-g2</td>
<td>Flexible Global Ocean–Atmosphere–Land System Model gridpoint, version 2.0</td>
</tr>
<tr>
<td>FIO-ESM</td>
<td>First Institute of Oceanography (FIO) Earth System Model (ESM)</td>
</tr>
<tr>
<td>GFDL-CM3</td>
<td>Geophysical Fluid Dynamics Laboratory Climate Model, version 3</td>
</tr>
<tr>
<td>GFDL-ESM2G</td>
<td>Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component</td>
</tr>
<tr>
<td>GFDL-ESM2M</td>
<td>Geophysical Fluid Dynamics Laboratory Earth System Model with Modular Ocean Model (MOM), version 4, component</td>
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<td>Goddard Institute for Space Studies Model E, coupled with the Hybrid Coordinate Ocean Model (HYCOM) ocean model</td>
</tr>
<tr>
<td>GISS-E2-H-CC</td>
<td>Goddard Institute for Space Studies Model E2, coupled with HYCOM and interactive terrestrial carbon cycle (and oceanic biogeochemistry)</td>
</tr>
<tr>
<td>GISS-E2-R</td>
<td>Goddard Institute for Space Studies Model E2, coupled with the Russell ocean model</td>
</tr>
<tr>
<td>GISS-E2-R-CC</td>
<td>Goddard Institute for Space Studies Model E2, coupled with Russell and interactive terrestrial carbon cycle (and oceanic biogeochemistry)</td>
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<tr>
<td>HadGEM2-AO</td>
<td>Hadley Centre Global Environment Model, version 2—Atmosphere and Ocean</td>
</tr>
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<td>HadGEM2-ES</td>
<td>Hadley Centre Global Environment Model, version 2—Earth System</td>
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<td>Institute of Numerical Mathematics Coupled Model, version 4.0</td>
</tr>
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<td>INGV-SXG</td>
<td>Istituto Nazionale di Geofisica e Vulcanologia, SINTEX-G</td>
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<td>L’Institut Pierre-Simon Laplace Coupled Model, version 4</td>
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<td>L’Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution</td>
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<td>IPSL-CM5A-MR</td>
<td>L’Institut Pierre-Simon Laplace Coupled Model, version 5A, mid resolution</td>
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<td>IPSL-CM5B-LR</td>
<td>L’Institut Pierre-Simon Laplace Coupled Model, version 5B, low resolution</td>
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<td>Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled</td>
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<td>MPI-ESM-LR</td>
<td>Max Planck Institute Earth System Model, low resolution</td>
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<tr>
<td>NorESM1-M</td>
<td>Norwegian Earth System Model, version 1 (intermediate resolution)</td>
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<tr>
<td>NorESM1-ME</td>
<td>Norwegian Earth System Model, version 1 with carbon cycling (and biogeochemistry)</td>
</tr>
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Fig. 1. CESM1(CAM5) component models and coupling (Hurrell et al. 2013). All components were run at ~1° horizontal resolution. CESM1(CAM5) consists of coupled atmosphere (CAM5, 30 vertical levels), ocean [Parallel Ocean Program, version 2 (POP), 60 vertical levels], land [Community Land Model, version 4 (CLM4)], and sea ice [Los Alamos Sea Ice Model (CICE)] component models.

potential temperature and salinity data. The PHC2 dataset represents a blending of the Levitus et al. (1998) with Steele et al. (2001) data for the Arctic Ocean. Ocean biogeochemical tracers were initialized from a separate 600-yr spinup.

Our 1850 ocean initialization strategy leverages two assumptions. First, the upper ocean equilibrates on much shorter time scales than the deep ocean. Therefore, the upper ocean adjusts to a preindustrial state after several decades under constant forcing. Second, modern observations still reflect preindustrial conditions at depth because of the long abyssal ocean equilibrium time scales. After an expected initial surface ocean cooling, the 1850 control arrived at a balanced coupled state with climate drift only in the deep ocean (global ocean temperature drift of ~0.005 K century⁻¹ for years 400–1000).

After a few centuries, the control run climate was in quasi equilibrium with the 1850 forcing. At this point, we started the first ensemble member using initial conditions from a randomly selected date in the 1850 control run: 1 January, year 402 (Table 1). Ensemble member 1 was integrated forward from 1850 to 2100 (Fig. 2). Ensemble members 2–30 were all started on 1 January 1920 using slightly different initial conditions (Table 1). Spread in ensemble members 3–30 was generated by round-off level differences in their initial air temperature fields. Specifically, we applied random round-off level (order of 10⁻¹⁴ K) differences to the air temperature field of ensemble member 1 to generate atmospheric initial conditions for ensemble members 3–30. With the exception of their initial air temperature field, ensemble members 3–30 all had the same initial conditions. For technical reasons, ensemble member 2 was started using a 1-day lagged ocean initial condition. Because all 30 CESM-LE members share essentially the same ocean initial conditions, the CESM-LE does not sample internal climate variability resulting from differing ocean states.

All CESM-LE ensemble members have the same specified external forcing. Following the CMIP5 design protocol, we applied historical forcing from 1920 to 2005 (Lamarque et al. 2010) and representative concentration pathway 8.5 (RCP8.5) forcing (Meinshausen et al. 2011; Lamarque et al. 2011) from 2006 to 2100. Unlike the CMIP5 CESM runs, which specified ozone forcing from the CAM-Chem model (“CMIP5 CESM ozone”; Lamarque et al. 2010, 2011; Meehl et al. 2012), the CESM-LE simulations use ozone concentrations calculated by a high-top coupled chemistry–climate model {CESM1[Whole Atmosphere Community Climate Model (WACC)]; Marsh et al. 2013} with specified ozone depleting substances (Table 1).

In response to the applied historical and RCP8.5 external forcing from 1920 to 2100, the global surface temperature increases by approximately 5 K in all ensemble members (Fig. 2). This consistent ~5-K global warming signal in all ensemble members by year 2100 reflects the climate response to forcing and
feedback processes as represented by this particular climate model. In contrast, internal variability causes a relatively modest 0.4-K spread in warming across ensemble members. The global surface air temperature evolution in the CESM-LE simulations is similar to that in CMIP5 CESM1(CAM5) experiments contributed to CMIP5 (Meehl et al. 2013).

Completing the CESM-LE simulations required substantial computational, storage, and human resources. The CESM-LE is a “big data” project for the current generation of computing. All CESM-LE simulations were run on Yellowstone, NCAR’s high-performance computing resource. Each CESM-LE member (1920–2100) took ~3 weeks to complete and produced 6.6 TB (15.3 TB) of postprocessed (raw) output. When combined with the preindustrial controls, a total of over 17 million Yellowstone core hours in over 1,500 individual jobs were required to complete the CESM-LE simulations. The total postprocessed archived data volume for the CESM-LE simulations (200+ TB) exceeds the entire CESM-to-complete the CESM-LE simulations. The total postprocessed archived data volume for the CESM-LE simulations (200+ TB) exceeds the entire CESM contribution to CMIP5 (~170 TB).

The CESM-LE outputs are publicly available via the Earth System Grid (ESG; www.earthsystemgrid.org) as single-variable time series in self-documenting lossless compressed netCDF-4 format. All saved outputs—including variable names, units, and frequency—are detailed on the CESM-LE website. A unique aspect of the CESM-LE is the large number of high-frequency fields that have been saved. Continuous daily outputs will be useful for studying extremes on socially relevant time scales. The 6-hourly outputs during three 10-yr periods (1996–2005, 2025–34, and 2071–80) enable cyclone tracking and can serve as boundary conditions for regional climate model simulations, among other applications. Of interest to those planning offshoot experiments, the files required to restart CESM are saved every five years in all ensemble members. The experimental design for the CESM-LE project is reproducible. The code base and associated external forcing files are also available on the Earth System Grid.

ILLUSTRATIVE RESULTS AND THE QUESTIONS THEY INSPIRE. With the ensemble experimental design described, we next present thought-provoking initial results from the CESM-LE. We begin with global-mean surface air temperature trends. Global-mean trends are less affected by internal climate variability than regional trends. Yet, the influence of internal climate variability on global trends has recently emerged as an important research topic because of the observed global surface warming “hiatus” or the reduction in the rate of global surface air temperature increase since the mid-1990s (Tollefson 2014; see Fig. 2).

One leading hypothesis for the global warming hiatus implicates internally generated, deep ocean heat uptake. While the surface ocean cools, the deep ocean traps heat and thus warming decelerates (Meehl et al. 2011; Kosaka and Xie 2013; Trenberth and Fasullo 2013; England et al. 2014; Clement and Dinezio 2014). Another hypothesis posits that increased stratospheric aerosol from volcanic eruptions contributes to the hiatus (Solomon et al. 2011; Neely et al. 2013; Santer et al. 2014). The CESM-LE can help address the causes of global surface warming acceleration and deceleration. For example, how do modes of coupled internal climate variability and external forcing jointly affect global warming trends, and what mechanisms are involved?

To illustrate the influence of internal climate variability on global warming trends in the CESM-LE, Fig. 3 shows histograms of 10- and 20-yr global surface air temperature trends for the preindustrial (1850), the present (1990–2009), and the near future (2030–49). The preindustrial control run has constant 1850 forcing, a balanced top-of-atmosphere energy budget, and negligible climate drift. As a result, the 10- and 20-yr preindustrial trend histograms are symmetric about 0 (no trend). Even with a stable mean climate, there is a range in preindustrial trend magnitudes (e.g., –0.2 to +0.2 K decade\(^{-1}\) for 20-yr trends). This range is a measure of unforced internally generated climate variability, and the size of this range depends on the length of the interval over which trends are computed (e.g., Hunt and Elliot 2006). For example, the largest 10-yr trends are approximately twice the magnitude of the largest 20-yr trends.

By the late twentieth century/early twenty-first century, global warming has occurred in all ensemble members (Fig. 2), and the majority of the 10-yr and all of the 20-yr trends are positive (Fig. 3). Like the preindustrial, there is a considerable range of warming rates because of the internal climate variability. Of interest to hiatus research, recently observed 10- and 20-yr global surface air temperature trends are within the trend spread predicted by the CESM-LE ensemble members. In other words, the observed global warming hiatus is within the lower end of the range of plausible global warming responses to historical forcing as predicted by this particular climate model. Looking to the future, cooling trends become increasingly unlikely. Indeed, while a range in trend magnitude remains, 10- and 20-yr cooling trends no longer occur in the mid-twenty-first century under RCP8.5 forcing. In summary, initial analysis of the
Fig. 3. Histograms of 10- and 20-yr trends in global surface air temperature for the 1850 control (black), starting from 1990 to 2009 (blue) and starting from 2030 to 2049 (red). Trends were calculated using time series of monthly mean values. The number of trends contributing to each histogram is not identical. For the 1850 control, independent continuous 10- and 20-yr segments were used to calculate trends. For the 1990–2009 and 2030–49 periods, trends were calculated for every possible start year. For example, for the period 1990–2009, 10-yr trends were calculated using Jan 1990–Dec 1999, Jan 1991–Dec 2000, … , Jan 2009–Dec 2018, while the 20-yr trends were calculated as Jan 1990–Dec 2009, Jan 1991–Dec 2010, … , Jan 2009–Dec 2028. Observed ranges are from HadCRUT4 (Morice et al. 2012) and Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP; Hansen et al. 2010). Observed trend minimum–maximum ranges were based on 10-yr trends calculated from Jan 1990–Dec 1999, Jan 1991–Dec 2000, … , Jan 1994–Dec 2013 and on 20-yr trends calculated from Jan 1990–Dec 2009, Jan 1991–Dec 2010, … , Jan 1994–Dec 2013.
CESM-LE global temperature trends supports existing research showing that global-mean surface air temperatures can show no trend or even slight cooling in the presence of long-term warming (e.g., Easterling and Wehner 2009), but unlike previous studies based on ensembles of opportunity that mix together climate model differences and internal variabilities, the CESM-LE shows that internal variability alone can generate substantial spread in global warming trends.

Having shown that internal climate variability can exert a substantial influence on global-mean temperature trends, we next look regionally, where we expect the influence of internal climate variability to be even larger. In particular, we use trend maps to illustrate the "single realization problem," the fact that any individual climate trajectory deviates from the mean forced response (e.g., Bengtsson et al. 2006; Easterling and Wehner 2009). Figure 4 shows boreal winter [December–February (DJF)] surface air temperature trends over the era with the best global observational coverage (1979–2012). The ensemble mean, an estimate of the forced response, depicts the familiar patterns of Arctic amplification and more warming over land than over the ocean. While the ensemble mean is useful for identifying the forced climate response, comparing across the individual ensemble members illustrates that the forced response is rarely realized. Why? The CESM-LE members show that regional trends can vary dramatically in magnitude and sign because of the internal climate variability. For example, the East Coast of the United States warms by about 3 K over the period 1979–2012 in ensemble member 6 but cools by about 3 K over the same period in ensemble member 13. Similarly, much of Eurasia cools by nearly 2 K in member 7, while the same region warms by about 3 K in member 17. The difference between ensemble member 6 and 13, and between 7 and 17, is the result of internal climate variability that cannot be predicted from initial condition differences at 1920.

Like any individual model ensemble member, the observations also represent one possible response of the climate system to external forcing in the presence of internal climate variability. As a consequence, comparing trends from a single ensemble member to the observed 1979–2012 temperature trends to “validate” the climate model simulation is problematic. Similarly problematic is comparing the ensemble-mean trend to observations, as internal climate variability is (by construction) muted in the ensemble mean. To confound matters even further, the available observations in some regions are too sparse to reliably detect a trend from observations alone (e.g., mountainous and polar regions in the Hadley Centre Climatic Research Unit temperature (HadCRUT4) dataset (Morice et al. 2012)).

When no ensemble member is able to reproduce the observed trend or when the trends in all ensemble members look more similar to each other than they do to the observed trend, the question becomes have we detected a model bias or have we inadequately sampled the ensemble spread? For example, none of the CESM-LE ensemble members replicate the magnitude of the observed surface cooling in the Southern Ocean or the eastern tropical Pacific over recent decades. For the Southern Ocean, the lack of surface cooling trends in the CESM-LE is consistent with associated weak ocean heat uptake in CESM1(CAM5). For the eastern tropical Pacific, the lack of pronounced surface cooling in the CESM-LE is directly relevant to hiatus research. Namely, the inability of any ensemble member to replicate the observed magnitude of the tropical Pacific Ocean surface cooling suggests that the tropical Pacific Ocean hypothesis [i.e., as tested by Kosaka and Xie (2013)] is not the only mechanism contributing to decelerated warming rates in the CESM-LE.

While the comparison of models and observations provides important insights, climate change projections are made in part to plan for a future we cannot observe. As such, we next examine the influence of internal climate variability on near-future trends, looking forward as far as we looked backward (i.e., 34 yr). Similar to Fig. 4, Fig. 5 shows that most CESM-LE members exhibit 2013–46 warming trends in most regions, with the exception of the North Atlantic. Yet, in some ensemble members, the internal climate variability is large enough to overwhelm the forcing and result in cooling in some regions. For example, ensemble member 20 shows pronounced cooling of 3 K over Asia that is in stark contrast to the appreciable warming of 6 K in that same region in ensemble member 24. The take-home message is clear, consistent with previous studies analyzing large ensembles with the same model and the same external forcing, and needs to be better communicated (e.g., Deser et al. 2012a): we need to plan for a range of future outcomes not only because climate models imperfectly represent the relevant processes, but also because there are inherent predictability limits in a climate system with large internal climate variability.

**Comparison to CMIP5.** CMIP5 is frequently used to assess uncertainty in future climate projections. But CMIP5 is an ensemble of opportunity, and the spread within the CMIP5 archive is not easy to interpret. Individual CMIP5 ensemble members can have differing physics, dynamical cores, resolutions,
Fig. 4. Global maps of historical (1979–2012) boreal winter (DJF) surface air temperature trends for each of the 30 individual CESM-LE members, the CESM-LE ensemble mean (denoted EM), and observations (denoted OBS based on GISTEMP; Hansen et al. 2010).
Fig. 5. Global maps of near-future (2013–46) boreal winter (DJF) surface air temperature trends for each of the 30 individual CESM-LE members and the CESM-LE ensemble mean (denoted EM).
and initial conditions. To complicate matters, many CMIP5 models share genes and are therefore not independent (Knutti et al. 2013). In sum, spread in CMIP5 climate projections results both from model formulation differences and from internal climate variability, the relative importance of which is unknown. Unlike the CMIP5 ensemble spread, CESM-LE ensemble spread is generated by internal climate variability alone. Given these points, a natural question becomes how much of the spread in CMIP5 projections can be explained by internal climate variability alone? We can answer this question by using the CESM-LE to estimate the influence of internal climate variability on ensemble spread.

Figure 6 shows spread in DJF surface air temperature trends during the preindustrial, historical, and near-future periods. We quantify spread for both the CESM-LE and CMIP5 using the standard deviation in 34-yr trends. Surprisingly, similar trend spread patterns and magnitudes are evident in the CESM-LE regardless of the time period selected. Reinforcing the visual similarity of the CESM-LE trend variability in all three periods (1850, 1979–2012, and 2013–46), statistically different trend variability is rare (i.e., few regions are stippled in the CESM-LE panels in Fig. 6). These comparisons suggest that internal climate variability in this particular variable and time span is largely independent of forcing. In other words, the influence of forced climate change on internal climate variability in 34-yr DJF surface air temperature is small. This result has practical relevance. Indeed, when internal climate variability does not change under climate forcing, long control runs and large forced ensembles will provide similar estimates of internal climate variability. Of even greater interest in Fig. 6, the trend spread generated by internal climate variability alone—estimated using the CESM-LE—is often statistically indistinguishable from the spread in trends within CMIP5. At least for DJF surface air temperature trends, the conclusion is stunning: CMIP5 spread in many regions (i.e., regions that are not stippled in the CMIP5 panels in Fig. 6) can be explained by internal climate variability [as estimated by CESM(CAM5)] alone.

While the trend variability comparisons in Fig. 6 are interesting, the implications are not universal. The contribution of internal climate variability to ensemble spread depends on the climate variable, time period, season, and location (e.g., Deser et al. 2012b). What is the relative contribution of model formulation differences and internal climate variability to changes in other climate variables? Why are there differences across climate variables, time periods, seasons, and locations?

Where should we expect improved model formulations to reduce spread in future climate projections? These are the types of important climate questions that can be addressed by comparing CESM-LE and CMIP5 ensemble spread.

**EXTREMES.** Understanding extreme climate phenomena requires multiple realizations for adequate statistical sampling. To illustrate the utility of the CESM-LE for studying extreme climate phenomena, we next focus on detecting changes in the climatologies of extreme events. In particular, we analyze atmospheric blocking changes produced by differences in model physics and heat stress changes resulting from twenty-first-century RCP8.5 forcing.

Atmospheric blocking is often associated with extreme events in the midlatitudes. Under blocked atmospheric flow, persistent winter cold spells and summer heat waves occur. On the periphery of blocked regions, atypical weather patterns can also lead to surface temperature and precipitation extremes. Because blocking is a feature in the large-scale atmospheric flow, it is a relatively reliable proxy for extreme events in climate model simulations. Yet, blocking statistics have appreciable year-to-year variability and thus many years of data are needed to attribute changes in blocking statistics to model differences or to external forcing.

To illustrate the unique value of large ensembles for evaluating blocking climatologies, Fig. 7 compares Northern Hemisphere blocking frequency (D'Andrea et al. 1998) in the 30-member CESM-LE; a 30-member Community Climate System Model, version 4 (CCSM4) ensemble (Mudryk et al. 2014); and historical reanalysis. Substantial longitudinally dependent ensemble spread in climatological blocking frequency is evident in both 30-member ensembles, a finding that demonstrates the importance of large ensembles for evaluating mean state model blocking climatologies. Comparing the 30-member CCSM4 ensemble to the 30-member CESM-LE, we can confidently attribute blocking statistics differences to model physics differences. Specifically, the CESM-LE exhibits increased and improved blocking frequency over the Atlantic (30°W–15°E) when compared to CCSM4. Interestingly, the ensemble spread in the CESM-LE is greater than that in the CCSM4 ensemble over the eastern Atlantic (0°–30°E), hinting not only at differences in climatological-mean blocking but also in blocking variability.

Heat stress is a leading cause of weather-related human mortality and morbidity (Guirguis et al. 2014; CDC 2006). When the climate warms, heat stress...
Fig. 6. Global maps of standard deviation in 34-yr DJF surface air temperature trends for the (top) preindustrial (1850), (middle) historical (1979–2012), and (bottom) near-future (2013–46) periods. For the historical and near-future periods, trends are shown for both the 30-member CESM-LE ensemble and the 38-member CMIP5 ensemble (Taylor et al. 2012). Stippling on the historical and near-future CESM-LE trend maps indicates standard deviations that are statistically different than the CESM-LE preindustrial period. Stippling on the historical and near-future CMIP5 maps indicates standard deviations that are statistically different than the CESM-LE for the corresponding period. Stippling is based on an f test and a 95% confidence interval. For CMIP5, we used a single (the first) ensemble member of the following models (see Table 2 for full list of expansions): ACCESS1.0, ACCESS1.3, BCC_CSM1.1(m), BCC_CSM1.1, BNU-ESM, CanESM2, CCSM4, CESM1(BGC), CESM1(CAM5), CESM1(WACCM), CMCC-CM, CMCC-CMS, CNRM-CMS, CSIRO Mk3.6.0, EC-EARTH, FGOALS-g2, FIO-ESM, GFDL CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-H-CC, GISS-E2-R, GISS-E2-R-CC, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INM-CM4.0, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-LR, MRI-CGCM3, NorESM1-M, and NorESM1-ME.
worsens in severity (e.g., hotter days and nights), frequency (number of hot days and nights), and duration (heat waves) (Meehl and Tebaldi 2004). At the same time, determining heat stress patterns and trends is not straightforward because of the wide variety of methodological approaches in defining a heat wave (Smith et al. 2013) and because of the internal climate variability (Perkins and Fischer 2013; Fischer et al. 2013). Daily outputs from the CESM-LE can be used to identify the mechanisms underlying regional differences in future heat stress projections (e.g., connection to atmospheric blocking or land–atmosphere feedbacks) and to assess the influence of internal climate variability on heat stress metrics. To illustrate the value of the large ensemble for the latter, Fig. 8 contrasts early twenty-first-century heat stress changes in all 30 CESM-LE members with corresponding changes in one randomly selected ensemble member (ensemble member 6). Over the early twenty-first century, heat wave intensity, duration, and frequency increase everywhere, but with regional magnitude differences. When all 30 ensemble members are used to detect heat stress changes, the results are statistically significant nearly everywhere. In contrast, the heat stress changes in ensemble member 6 are much less likely to be statistically significant and differ from the 30-member mean changes because of the unique expression of internal climate variability in this particular ensemble member.

**NEW ANALYSES ENABLED.** Reflecting the demand for an open-access large ensemble and community participation in the CESM-LE experimental design, analysis of CESM-LE simulations has already begun and interest is expected to grow. Using the CESM-LE framework, it is possible to cleanly separate forced climate change from internally generated variability, to quantify model projection spread, and to evaluate how variability coevolves with a changing climate. Research evaluating urban heat waves, atmospheric circulation and blocking, precipitation characteristics, snow cover, ozone hole impacts, air quality, Greenland Ice Sheet surface mass balance, sea ice, and hurricanes has already begun. Biogeochemical processes are being analyzed in a large ensemble framework for the first time including uptake and storage of anthropogenic carbon dioxide by the land and ocean, primary productivity by biology in the land and ocean, and variation of atmospheric carbon dioxide on seasonal to decadal time scales. Offshoot experiments have already started including experiments to test the competing hypotheses for hiatus periods, to evaluate hurricanes in CESM1(CAM5) using high-resolution time slice experiments, to force regional downscaling simulations, and to run a complementary ensemble under RCP4.5 forcing to assess avoided impacts. To help coordinate community analysis of the CESM-LE, we are compiling
Fig. 8. Maps of early twenty-first-century change (2040s–2010s) in heatwave intensity, duration, and frequency from the CESM-LE for (left) 30 ensemble members and for (right) 1 ensemble member. Heat waves are defined following Meehl and Tebaldi (2004). Heat wave intensity, duration, and frequency were calculated for each year and then averaged. Hatching indicates differences are not statistically significant at the 95% level using a Student’s t test.

A list of all ongoing projects at the CESM-LE website (www2.cesm.ucar.edu/models/experiments/LENS). A new resource useful for analyzing the CESM-LE, and for making comparisons to CMIP5, is the freely available Climate Variability Diagnostics Package (Phillips et al. 2014).
SUMMARY AND BROADER IMPLICATIONS.
Understanding forced climate change in the presence of internal climate variability is a major challenge for climate prediction. To make progress, the science and stakeholder communities need relevant climate model experiments with useful outputs. The CESM-LE addresses this challenge through its transparent experimental design and relevant accessible outputs. Initial illustrative CESM-LE results affirm that because of the internal climate variability, single realizations from climate models are often insufficient for model comparison to the observational record, model intercomparison, and future projections. A publicly available ensemble with the scope, and the amount of community input as the CESM-LE, has never been performed before. We anticipate analysis of this ensemble, alone or in combination with other ensembles and/or regional climate simulations, will lead to novel and practical results that will inspire probabilistic thinking and inform planning for climate change and climate model development for many years to come.

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Science at Your Fingertips
This work documents the fidelity of the newly developed Indian Institute of Tropical Meteorology climate model simulations and demonstrates its suitability to address the climate variability and change issues relevant to the South Asian monsoon.

The Indian Ministry of Earth Sciences and the National Oceanic and Atmospheric Administration (NOAA) entered into a formal agreement to collaborate on the implementation of the National Centers for Environmental Prediction (NCEP) weather and seasonal prediction system in India during 2011. As part of this collaboration, the India Meteorology Department (IMD) and National Centre for Medium Range Weather Forecasts (NCMRWF) implemented the high-resolution (T574, L64) atmospheric Global Forecast System (GFS) model with three-dimensional variational data assimilation (3DVAR) at IMD for short- and medium-range weather forecasts. Also, the coupled ocean–atmosphere model, Climate Forecast System version 2 (CFSv2), with a high-resolution atmosphere (T382, L64), was implemented for seasonal prediction at the Indian Institute of Tropical Meteorology (IITM). To address the long-term critical need in India for a climate model that would provide reliable future projections of Indian monsoon rainfall, IITM planned on building an Earth system model (ESM) based on the CFSv2 framework. Further, as part of the Monsoon Mission (see www.tropmet.res.in/), India is committed to improving the CFSv2 model for providing more skillful predictions of seasonal monsoon rainfall, which would also benefit the short- and medium-range predictions at IMD. Therefore, the extension of the seasonal prediction model to a long-term climate model would establish a seamless prediction system from weather time scales to seasonal...
and decadal time scales in India. In this paper, we describe how the seasonal prediction model has been converted into a model suitable for long-term climate studies.

The NCEP CFS (Saha et al. 2006), the predecessor of the CFSv2, has been used to provide coupled ocean–atmospheric forecasts since 2004, demonstrating good skill in simulating and predicting El Niño–Southern Oscillation (ENSO) (Wang et al. 2005; Zhang et al. 2007) and the South Asian summer monsoon variability (Achuthavarier and Krishnamurthy 2010; Yang et al. 2008; Pattanaik and Kumar 2010; Chaudhari et al. 2013; Pokhrel et al. 2012, 2013). With substantial changes compared to CFSv1, the CFSv2 (Saha et al. 2014) demonstrated better prediction skill for ENSO, the tropical Atlantic sea surface temperatures (SST), global land precipitation, surface air temperature, and the Madden–Julian oscillation (Yuan et al. 2011; Weaver et al. 2011; Jiang et al. 2013; Hu et al. 2013). Importantly, exhaustive hindcast experiments on seasonal and extended time scales carried out at IITM demonstrated that the CFSv2 model was one of the few models that predicted the general distribution of Indian summer monsoon rainfall during June–September (henceforth ISMR) and its intraseasonal and interannual variability with statistically significant skill (Roxy et al. 2012; Chaudhari et al. 2013).

To address issues related to longer time-scale climate variability, beyond the seasonal time scale, a climate model needs to simulate the observed mean climate reasonably well. Moreover, for a region like South Asia, a realistic simulation of the climatology and variability of the ISM and the drivers of its variability is imperative. Equally important is the ability to replicate the observed sensitivity in temperature to the increasing greenhouse gases (GHGs). However, despite its good seasonal prediction skill, several 100-yr simulations carried out at IITM demonstrated a cold bias in global mean temperature and a lack of the observed sensitivity to GHG increases in CFSv2, limiting its utility as a climate change model (e.g., Roxy et al. 2012). The model also exhibits a dry bias over the Indian subcontinent during the June–September (JJAS) monsoon season, along with colder-than-observed SSTs in the Arabian Sea (Roxy et al. 2013) and eastern tropical Indian Ocean (Chaudhari et al. 2013). Roxy et al. (2012) also noticed a systematic bias in the thickness of the mixed layer in the ocean component of CFSv2. While model systematic biases tend to affect the simulation of long-term mean climate as well as long-term projected trends, improved representation of oceanic processes is one approach to aid in minimizing systematic biases (see Semtner and Chervin 1992). For example, such an effort has substantially improved the simulation of many key climate features in GFDL CM2.5 (Delworth et al. 2012), a state-of-the-art model. These works provide motivation for the possible alleviation of systematic biases in the CFSv2 model through improved representation of ocean processes in the coupled model.

As a first step toward adapting the CFSv2 as an ESM, an ocean model with biogeochemistry, and a better physics scheme for improving the biases of the current ocean component in CFSv2, was incorporated. In this study, we document the formulation of the IITM-Earth System Model version 1 (IITM-ESMv1), and discuss improvements in simulations of various important ocean–atmospheric processes and variability.

The paper is organized as follows. Section 2 describes the model configuration, coupling strategy, experimental design, and initialization details of the climate simulations. Section 3 presents a comparative assessment of the simulated annual mean climate, and biases therein, between the simulations of CFSv2 and ESMv1. Section 4 describes the fidelity of simulated ENSO and Pacific decadal oscillation (PDO) patterns, dominant modes of climate variability on interannual and decadal scales, and teleconnection of ENSO to ISM. The results are summarized in section 5.

**BRIEF DESCRIPTION OF THE IITM-ESMv1.** The IITM-ESMv1 has been developed by replacing the Modular Ocean Model ocean component (MOM4p0; Griffies et al. 2004) of the CFSv2 with MOM4p1 (Griffies et al. 2009) and retaining the land and atmosphere components. MOM4p1 has better physics compared to MOM4p0, as well as an interactive ocean biogeochemistry (BGC) component (Dunne et al. 2012). The major differences between the ocean components of IITM-ESMv1 and CFSv2 are summarized in the online supplement to this paper (available at http://dx.doi.org/10.1175/BAMS-D-13-00276.2).

**Ocean and sea ice components.** The ocean component (MOM4p1) in IITM-ESMv1 is a hydrostatic model using Boussinesq approximation and has a rescaled geopotential vertical coordinate (Stacey et al. 1995; Adcroft and Campin 2004) for a more robust treatment of free surface undulations. Key physical parameterizations include a KPP surface boundary layer scheme similar to that of Large et al. (1994), which computes vertical diffusivity, vertical viscosity, and nonlocal transport as a function of the flow and surface forcing. Griffies et al. (2009) provide
a detailed description of the model equation, physics, dynamics, time-stepping schemes, and further subgrid-scale parameterizations.

The IITM-ESMv1 ocean model has 40 vertical levels from the surface to 4500 m, identical to that of the CFSv2. It has 27 levels in the upper 400 m of the water column in an attempt to capture surface boundary layer processes. Bottom topography is represented by the partial cell method described by Adcroft et al. (1997) and Pacanowski and Gnanadesikan (1998). Both the ocean and sea ice models use the Arakawa B grid (Arakawa and Lamb 1977). The zonal resolution is 0.5° and the meridional resolution is 0.25° between 10°S and 10°N, becoming gradually coarser through the tropics, up to 0.5° poleward of 30°S and 30°N. The use of the Murray (1996) bipolar grid facilitates the removal of the coordinate singularity from the Arctic Ocean domain.

The sea ice component of IITM-ESMv1 is the Geophysical Fluid Dynamics Laboratory (GFDL) Sea Ice Simulator (SIS; Delworth et al. 2006; Winton 2000), which is an interactive dynamical sea ice model with three vertical layers, one snow and two ice, as well as five ice thickness categories.

**Atmosphere and land components.** The atmospheric component of IITM-ESMv1 is based on the NCEP GFS model and has a spectral triangular truncation of 126 waves (T126) in the horizontal (~0.9° grid) and finite differencing in the vertical with 64 sigma-pressure hybrid layers. It employs the simplified Arakawa–Schubert convection scheme, with cumulus momentum mixing. The land surface model (LSM) is the Noah LSM, with four layers (Ek et al. 2003), as in CFSv2. Further details can be found in Saha et al. (2010).

**Coupling and initialization.** The component models pass fluxes across their interfaces through an exchange grid system, which enforces the conservation of energy, mass, and tracers. The atmosphere, land, and sea ice exchange quantities such as heat and momentum fluxes every 10 min, with no flux adjustment or correction. The ocean tracer and atmosphere–ocean coupling time step is 30 min. The individual model components were initialized with 1 December 2009 initial conditions derived from the NCEP CFS reanalysis. The model has been integrated forward for a 100-yr period without any changes in radiative forcing. Importantly, the biogeochemistry and ecosystem modules were switched off to facilitate a comparison of the simulated climate statistics with those from the CFSv2. For convenience, we refer to this simulation as the ESMv1 run. For comparison, we utilize the results from a 100-yr run we carried out earlier with the CFSv2, which also started with the same set of initial conditions. Unless specified, the last 50 yr of the simulations from both models are used for the comparison.

**Observation-based datasets used for evaluating the simulations.** For the evaluation of the model simulations, we use the SST data from the 2009 version of the *World Ocean Atlas* (WOA; Locarnini et al. 2010) and density-based mixed layer depth data (de Boyer Montégut et al. 2004). We also use the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST1.1) (Rayner et al. 2003), gridded rainfall data from IMD (Rajeevan et al. 2006) for the period 1930–2010 and gridded monthly rainfall data from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI; Huffman et al. 2007) for 1998–2012, and the NCEP–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) circulation fields for the period 1980–2010. Global surface air temperature anomalies are obtained from National Aeronautics and Space Administration (NASA) (Hansen et al. 2006), for the period of 2000–2010, and sea ice concentration data from HadISST (Rayner et al. 2003) for the period 1950–2010 are also utilized for the study.

The climatologies for the ESMv1 and the CFSv2 are computed for the last 50 yr of simulation. The simulated biases for any variable are computed by subtracting the observed value from the corresponding simulated value. The statistical significance of the bias is estimated based on a two-tailed Student’s t test.

**MEAN STATE IN ESMv1.** Annual mean surface temperature and SST. The time evolution patterns of the global mean annual mean surface temperature and SST using ESMv1 and CFSv2 are examined (Fig. 1). During the initial 30 yr of the 100-yr run, the CFSv2 simulations undergo a rapid cooling from a global mean surface temperature ($T_s$) of 14.4°–13°C (Fig. 1a) and stay close to that range thereafter. This value is substantially less than the observed global $T_s$ of 14.6°C (Hansen et al. 2006), indicating a bias of at least 1.6°C in the simulated global surface temperature. However, the initial cooling of simulated $T_s$ by the ESMv1 is nearly about 0.6°C (Fig. 1a), and the $T_s$ remains around 14.2°C thereafter. Importantly, the drift in the SST simulated by the ESMv1, averaged globally or in the tropics, is only about 0.4°C, as compared to an SST bias of 1.4°C in CFSv2 (Figs. 1b and 1c).
The results confirm a significant reduction in cold bias in the tropics between 30°S and 30°N, also as evidenced by the RMSEs of 0.79 and 0.89 for ESMv1 and CFSv2, respectively. A similar reduction of the biases is seen in northern subtropical gyres. One of the potential reasons for the improved reduction in the cold bias in the regions of northern subtropical gyres in ESMv1 is the use of the parameterization for the effect of submesoscale mixed layer eddies (Fox-Kemper et al. 2011), which prevents mixed layer depths from becoming excessively deep [Hallberg (2003); see also Fig. 4a and discussion in the following section]. The improvements in ESMv1 have been further ascertained by comparing the simulations with the WOA (figures not shown).

In both of the models, particularly CFSv2, however, the cold bias lingers in the North Atlantic Current east of Newfoundland, which is a region of very sharp gradients in SST. Small errors in the paths of ocean boundary currents can lead to such large SST biases (Griffies et al. 2011). While there is a notable and a general improvement in the tropical SST simulation, the warm biases in the far-eastern Pacific cold tongue and in the Southern Ocean have increased. We also note that warm biases are found in the Southern Ocean and in the upwelling region off the western coast of South America (Figs. 2b and 2c) in both the models, particularly in the ESMv1. The simulated warm bias in the Southern Ocean in ESMv1 is higher compared to in CFSv2 and is due to the weaker-than-observed simulated lower-level zonal winds (figure not shown). A recomputation of the SST biases, after removing the mean global SST (figure not shown), indicates that the difference between ESMv1 and CFSv2 is mainly reflected in the mean, and the spatial patterns of both ESMv1 and CFSv2 are nearly the same, with a significantly high pattern correlation ($r = 0.9$), implying that the large-scale features in both the models remains the same. We note that most of the phase 5 of the Coupled Model

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**Fig. 1.** Time-evolution of the globally averaged annual mean fields (°C) of (a) near-surface temperature, (b) SST, and (c) tropical SST (30°S–30°N). The ESMv1 (CFSv2) simulations are in red (blue). The corresponding annual mean observational values are 14.6°, 18.6°, and 26.1°C, respectively.
Intercomparison Project (CMIP5) models exhibit similar biases with weaker-than-observed zonal winds in the Southern Ocean region (e.g., Fig. 5; Lee and Wang 2014).

**Mean precipitation.** The distributions of boreal summer monsoon (June–September) precipitation bias from ESMv1 and CFSv2 are shown in Fig. 3. The 10% level of statistical significance of the precipitation bias estimated based on a Student’s $t$ test is shown with contours in Fig. 3. Both CFSv2 and ESMv1 reproduce the observed precipitation patterns reasonably well, though they show larger-than-observed precipitation in the tropical western and eastern Pacific and the South Pacific convergence zone. However, there is improvement in the oceanic precipitation in ESMv1 in comparison with CFSv2, with a reduction in excess oceanic precipitation over the equatorial Maritime Continent region, the eastern equatorial Indian Ocean, and the western tropical Pacific Ocean, as compared to CFSv2.

Notwithstanding the improved SSTs in the tropical and northern Indian Ocean, the ESMv1 simulation also depicts a dry bias over India (Fig. 3b). In terms of interannual variability of the ISMR, the ESMv1 shows a climatological precipitation rate of 4.3 mm day$^{-1}$ with a standard deviation of 0.53 mm day$^{-1}$, giving a coefficient of variation (the variability in relation to the observed mean) of 9%. The corresponding statistics for the observations are 6 mm day$^{-1}$, 0.48 mm day$^{-1}$, and 8%, respectively. These results suggest a moderate improvement in the interannual variability of the land precipitation with respect to CFSv2, for which corresponding values are 4 mm day$^{-1}$, 0.5 mm day$^{-1}$, and 7.5%, respectively. The ESMv1 also shows slight improvement in terms of intensity and propagation characteristics of monsoon intraseasonal oscillation (figure not shown).

**Ocean mixed layer and subsurface characteristics.** One major difference between the ESMv1 and CFSv2 models is that the former employs Simmons et al.’s (2004) scheme for interior mixing along with mixed layer restratification by the submesoscale eddies (Fox-Kemper et al. 2008, 2011), as compared to the prescribed vertical diffusivity (Bryan and Lewis 1979) in the latter. To diagnose the role of such differences, we compare the simulated bias in annual mean ocean mixed layer depth (MLD) with respect to the observations (Fig. 4).

In general, the bias in the annual mean MLD is larger for CFSv2 (Fig. 4b) compared to ESMv1...
Significant improvement is seen in the tropical oceans, especially in the Arabian Sea and Bay of Bengal in the ESMv1 simulations. The 10% level of statistical significance of the MLD bias estimated based on a Student’s \( t \) test is shown with contours in Fig. 4. Notably, Roxy et al. (2012) found that large biases of MLD in CFSv2 in the Arabian Sea during the summer monsoon season lead to an exaggerated SST–precipitation relationship. Indeed, improvements in the ESMv1-simulated MLD and SST also reflect an improvement in the precipitation in the tropics (Fig. 3). We note, however, a deeper-than-observed MLD in the region of northern subtropical gyres, as well as shoaling in the southern ocean in simulations by both models (Figs. 4a and 4b). The Southern Ocean shoaling is relatively larger in the ESMv1 simulation and consistent with the warm SST bias over the region (Fig. 2b). Our subsurface analysis shows that the warmer temperatures extend deeper in CFSv2 than in WOA, and ESMv1, as shown by the position of the 4°C isotherm in the zonally averaged vertical profiles of temperature (Figs. 4c–e). This is also seen in all three major individual ocean basins (see Fig. S1 in the online supplement to this article). This implies that pumping of heat away from the surface into deeper layers of the ocean takes place in the CFSv2, resulting in the cooling at the surface and warming of the ocean below.

**DOMINANT PACIFIC MODES OF VARIABILITY AND INTERACTIONS WITH INDIAN SUMMER MONSOON.** The Pacific Ocean exhibits substantial temporal and spatial variability. The large size of the basin facilitates unique atmosphere–ocean interannual coupled variability in the tropics, which is manifested as the El Niño–Southern Oscillation (ENSO; Rasmusson and Carpenter 1983). ENSO affects global climate and weather conditions such as droughts and floods (Ropelewski and Halpert 1987; Trenberth et al. 1998; Wallace et al. 1998; Ashok et al. 2007) and has a significant impact on the Asian summer monsoon (Sikka 1980; Webster et al. 1998; Kumar et al. 1999; Krishnamurthy and Goswami 2000; Lau and Nath 2000; Ashok et al. 2004; Shukla 1995; Keshavamurty 1982). In this section, we evaluate the fidelity of the simulated ENSO and its interaction with the Indian summer monsoon. We also focus our attention on the fidelity of the simulated Pacific decadal oscillation (PDO). We use the last 75 yr of ESMv1 and CFSv2 simulations and qualitatively compared them with statistics from the 75 yr (1935–2010) of HadISST data.

**El Niño–Southern Oscillation (ENSO).** The largest observed SST variability (Fig. 5a) is localized...(Fig. 4a). Significant improvement is seen in the tropical oceans, especially in the Arabian Sea and Bay of Bengal in the ESMv1 simulations. The 10% level of statistical significance of the MLD bias estimated based on a Student’s \( t \) test is shown with contours in Fig. 4. Notably, Roxy et al. (2012) found that large biases of MLD in CFSv2 in the Arabian Sea during the summer monsoon season lead to an exaggerated SST–precipitation relationship. Indeed, improvements in the ESMv1-simulated MLD and SST also reflect an improvement in the precipitation in the tropics (Fig. 3). We note, however, a deeper-than-observed MLD in the region of northern subtropical gyres, as well as shoaling in the southern ocean in simulations (Sikka 1980; Webster et al. 1998; Kumar et al. 1999; Krishnamurthy and Goswami 2000; Lau and Nath 2000; Ashok et al. 2004; Shukla 1995; Keshavamurty 1982). In this section, we evaluate the fidelity of the simulated ENSO and its interaction with the Indian summer monsoon. We also focus our attention on the fidelity of the simulated Pacific decadal oscillation (PDO). We use the last 75 yr of ESMv1 and CFSv2 simulations and qualitatively compared them with statistics from the 75 yr (1935–2010) of HadISST data.

**El Niño–Southern Oscillation (ENSO).** The largest observed SST variability (Fig. 5a) is localized...
across the central-eastern equatorial Pacific, and is predominantly associated with the canonical ENSO. The models qualitatively reproduce the basic pattern of the observed SST anomaly variability. The coefficient of variation (contours) in Fig. 5 indicates that the interannual variability is about 5% of the mean in the observations and is well captured in ESMv1. However, the simulated variance in CFSv2 is significantly weaker as compared to the observations (Fig. 5c). The ESMv1, on the other hand, performs better both in terms of the magnitude and the extension of the variance maxima from the east through the date line in the equatorial Pacific (Fig. 5b). In the CFSv2 simulations, the maximum variance is confined mostly to the eastern portion of the eastern equatorial Pacific. This is consistent with slightly flattened thermocline slope from the central to eastern equatorial Pacific in CFSv2 compared to ESMv1 (Fig. 5d). However, it is to be noted that the ESMv1 slightly overestimates the westward extension of the variance in comparison with the observations and CFSv2. The thermocline is also relatively shallow in the west and deeper in the east for ESMv1, showing less improvement with respect to CFSv2.

To illustrate the fidelity of the spatial pattern of interannual variability associated with ENSO, the gravest EOF pattern for boreal winter (December–February) SST anomalies over the Pacific from the HadISST data and that from two models are presented in Fig. 6. The horseshoe pattern in the Pacific associated with the observed ENSO variability, with unipolar loadings in the central and eastern equatorial Pacific, and oppositely signed loadings west of the date line (Fig. 6a) is qualitatively captured by both of the models (Figs. 6b and 6c). The 31.5% variance explained by the EOF1 from the ESMv1 is reasonably close to the corresponding value of 37% from the observations. The corresponding explained variance from the CFSv2 is slightly smaller, at 29.5%.

The time-mean global wavelet spectrum from a wavelet analysis on the observed PC1, which is associated with ENSO, shows a broad peak in the range of 2–7 yr, with maximum power at ~5 yr (Fig. 7d). Both models capture this broad peak reasonably well (Figs. 7e and 7f). The ESMv1 also exhibits a decadal modulation of interannual variability (Figs. 7b and 7e), similar to the observations (Fig. 7a). Though longer time series are required to adequately characterize the ENSO (Wittenberg 2009), many of the simulated ENSO events appear to be episodic, spanning a range of frequencies over the course of one or two events.

**ENSO–monsoon relationship in the coupled simulations.** The ENSO–monsoon teleconnection, to a good extent, depends on the Walker circulation to deliver the Pacific SST signal to the Indian Ocean and Indian

![Fig. 4. Spatial maps of bias in annual mean mixed layer depth for (a) ESMv1 and (b) CFSv2. The model results are computed over the last 50 yr of the simulation. Biases are in meters. The contours represent the 10% level of the statistical significance based on a Student’s t test. (c) Vertical distribution of the global ocean zonal mean temperature (°C) from WOA. (d),(e) As in (c), but for the ESMv1 and CFSv2, respectively.](image-url)
land sector (Krishnamurti 1971; Shukla and Paolino 1983; Webster and Yang 1992). Hence, for a better representation of the Indian summer monsoon and its variability, a model should adequately reproduce the spatial, seasonal, interannual, and decadal aspects of the ENSO–monsoon connection.

We next compare the simulated ENSO–monsoon teleconnection in the climate simulations of ESMv1 and CFSv2 with one another and also with that from observations. Figure 8 shows the lead–lag correlation between the ISMR and the monthly Niño-3.4 index. This will give a general idea on the mean ENSO–monsoon relationship, though it may not hold for its interdecadal variability as the teleconnection changes on decadal time scales (e.g., Krishnamurthy and Goswami 2000; Kriplani and Kulkarni 1998). The observed simultaneous negative correlation (Shukla and Paolino 1983) between Niño-3.4 SST and ISMR, along with the peak correlation after the monsoon, is reasonably simulated by the ESMv1. However, in CFSv2 simulations, the negative correlations unrealistically start developing 12 months prior to the monsoon season. Further, the correlation peaks just at the beginning of the monsoon season, 2–3 months earlier than observed. In fact, this is a common problem among most of the climate models, including a significant number of CMIP3 and CMIP5 models (Jourdain et al. 2013; Achuthavarier et al. 2012).

To understand the spatial variability of rainfall associated with ENSO, we project the summer monsoon rainfall onto the PC1 obtained from the EOF analysis (Fig. 6) of the SST anomalies. The regression patterns from both of the simulations show (see Fig. S2) below normal rainfall over most of the Indian region, with an excess of rainfall over northeast India similar to the observed pattern (figure not shown) depicting the role of ENSO on the Indian summer monsoon cycle.

**Pacific decadal oscillation (PDO).** The PDO is the dominant mode of interdecadal variability in the Pacific characterized by warm SST anomalies near the equator and along the coast of North America and cool SST anomalies in the central North Pacific in its positive phase (Mantua et al. 1997; Zhang et al. 1997; Power et al. 1999). Studies have shown that the PDO-related interdecadal variability can modulate the ENSO

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**Fig. S2.** Standard deviation of interannual SST anomalies (°C, shaded) for (a) HadISST, (b) ESMv1, and (c) CFSv2. The coefficients of variation (%) are overlaid as contours. (d) Depth of the 20°C isotherm (m) in the equatorial Pacific (5°S–5°N) for WOA, ESMv1, and CFS2.
(Wang 1995) and the ENSO-related interannual variabilities. The PDO, with a periodicity of 20–30 yr, is shown to have significant impact on the climate around the Pacific Ocean and beyond (Krishnan and Sugi 2003; Power et al. 1999).

Following Mantua et al. (1997), we have performed an EOF analysis of detrended monthly SST anomalies over the domain 20°–60°N, 120°E–120°W for the last 75 yr of simulations to explore the simulated PDO signal. For comparison, an EOF analysis is also performed on HadISST data for the period 1935–2010 over the same domain. The EOF1 results from the model and observations are shown in Fig. 9. The EOF1 pattern from HadISST data explains about 30.3% variance, with a unipolar signal in the central North Pacific surrounded by the oppositely phased loadings hugging the west coast of North America (Fig. 9a). This is the distinguishing feature of the warm phase of the PDO (e.g., Fig. 1; Krishnamurthy and Krishnamurthy 2014). The corresponding EOF1 from the ESMv1 (Fig. 9b) captures the pattern and associated explained variance reasonably well. On the other hand, the analogous EOF1 for the CFSv2 (Fig. 9c) explains only 24.4% of the total variance, and the spatial pattern shows relatively weak negative loadings in the North Pacific. This may be associated with the strong cold SST bias in the subtropical Pacific.

A wavelet power spectrum analysis on the observed PC1 (Fig. 9) indicates a dominant, and statistically significant, power in the 16–32-yr band (Figs. 10a and 10d). The ESMv1 successfully reproduces this dominant peak (Figs. 10b and 10e). However, in the CFSv2 simulations, it is weaker and not statistically significant (Figs. 10c and 10f).

Further, a regression of the December–February surface winds onto the PC1 indicates enhanced counterclockwise wind stress anomalies over the North Pacific (see Fig. S3a) associated with the PDO. Such an association is also seen in the simulations from the ESMv1 (Fig. S3b). The location of the anticyclonic winds and their magnitudes are well simulated. However, the counterclockwise surface circulation is weaker in the CFSv2 simulations (Fig. S3c) as compared to the observations and ESMv1 simulation. These, along with weaker-than-observed westerlies over the subtropical Pacific and the southeasterlies over the North American coast, are consistent with a weak PDO signal.

**PDO and Indian summer monsoon.** Krishnan and Sugi (2003) suggest that a warm phase of PDO can amplify the impact of El Niño, resulting in the weakening of the Indian summer monsoon.
Krishnamurthy and Krishnamurthy (2014) have shown that the PDO is associated with deficit rainfall anomalies mainly north of 18°N, with stronger anomalies in eastern central India. Indeed, a regression of the observed boreal summer monsoon rainfall (Rajeevan et al. 2006), for the period 1935–2010, onto the concurrent PDO index from the HadISST (Fig. 11a) conforms to these earlier observational works. The corresponding results from the simulations (Figs. 11b and 11c) are in qualitative agreement with Fig. 11a. However, the regression pattern from the CFSv2 simulation shows a slightly weaker-than-observed signal.

**SUMMARY AND CONCLUSIONS.** This paper documents the development of the first prototype of the IITM Earth System Model (ESMv1). Derived from the NCEP CFSv2, this model is being developed to be used in studies of the detection, attribution, and projections of climate change and its impact on the South Asian region. The effort particularly involved, as a first step toward the development of the IITM ESM, inclusion of an ocean biogeochemistry and ecosystem module and improved physics by replacing the ocean component of the CFSv2. Simulations of 100 yr were performed with the ESMv1 and CFSv2, using the same initial conditions, and their results were compared. The new ocean formulation has led to a significant reduction in the cold atmospheric temperature bias (from 1.5° to 0.6°C) and SST bias as compared to that in the CFSv2. The improvement in SST is particularly prominent in the tropical Indian and Pacific Oceans. As a result, the precipitation over the tropical oceans has also improved considerably.

In addition, the simulations with IITM-ESMv1 also show improvements in the mean state and near-surface biases in the northern subtropical gyres as well, implying the role of ocean physics in the coupled climate simulations. Importantly, the model demonstrates a realistic global mean temperature and is reasonable sensitivity to the ambient CO2, an essential prerequisite for a climate model to be used for climate change studies.

In terms of the spatial pattern and the periodicity, the ESMv1 simulations of climate variability are more realistic as compared to those of NCEP CFSv2. An example is the simulated PDO signal in CFSv2, which is much weaker than that
observed. Importantly, the ENSO–monsoon relationship in CFSv2 shows an unrealistically strong, negative correlation maximum between the Indian summer monsoon rainfall and the Niño-3.4 index 6–9 months prior to the observations, which may result in unrealistic monsoon variations. This is a common problem in many of the CMIP5 models (Jourdain et al. 2013). However, the ESMv1 captures the observed concurrent negative simultaneous correlations between the monsoons and ENSO, as well as a reasonable lead–lag relationship between these two. All these features demonstrate the ability of the ESMv1 to capture the crucial monsoon–ENSO links, which are important in manifesting the interannual variability of the South Asian summer monsoon. A companion study (Shikha 2013) demonstrates that the ESMv1 also simulates a realistic evolution of the Indian Ocean dipole (Saji et al. 1999; Webster et al. 1999; Murtugudde 2000) and its variability (figure not shown).

A preliminary analysis of the simulated Atlantic meridional overturning circulation (AMOC) indicates (figure not shown) that the full AMOC has not been yet established in the simulation and warrants the extension of the current integration by a few more hundreds of years. Such a longer run

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**Figure 8 (top).** Lead–lag correlations between all Indian summer monsoon years derived from the IMD datasets (June–September) rainfall and the monthly Niño-3.4 index from the HadISST [for the 1935–2010 period (black line)], ESMv1 (red line), and CFSv2 (blue line). Note that the model results are computed over the last 75 yr of the simulation for comparison.

**Figure 9 (bottom).** The leading EOF pattern of detrended monthly SST anomalies (°C) in the North Pacific (20°–60°N, 120°E–120°W) from (a) HadISST data for the period 1935–2010, (b) ESMv1, and (c) CFSv2. The model results are computed over the last 75 yr of the simulation.
will also result in more robust tropical climate statistics (e.g., Wittenberg 2009). We have also analyzed the distribution of sea ice concentration (Fig. S4) in the Northern Hemisphere from ESMv1 and CFSv2 for January–March (JFM) and June–September (JJAS). The Northern Hemisphere sea ice concentration in ESMv1 is comparable with HadISST data during JFM, the season when the sea ice coverage is largest in the Northern Hemisphere, but it is found to be lower than the observations during the boreal summer season (JJAS). Further, the Southern Hemisphere sea ice concentration is lower than observed (figure not shown) and more or less similar to that of the CFSv2. Importantly, Huang et al. (2015) note that the low sea ice concentration in CFSv2 has led to a weaker-than-observed AMOC in CFSv2, and improvement in sea ice concentration can be achieved by improving the sea ice albedo. Therefore, we plan to improve the sea ice parameters and also the coupling according to Huang et al. (2015) and extend the integration further to study the relevance of AMOC changes on the monsoon variability.

Even though the model’s fidelity, in terms of the mean climate and seasonal cycle simulations, are on par with those of some other state-of-the-art models, the model still has a few limitations, such as a warm bias in the Southern Ocean region, which are common across a wide spectrum of CMIP5 models (Lee and Wang 2014). Another important issue is that the CFSv2 has a top-of-the-atmosphere energy imbalance of 6 W m⁻², which is fairly constant over a 100-yr simulation (figure not shown). A similar signal is also associated with ESMv1. Since the temperature has stabilized, the imbalance could be due to some unaccountable source of energy that is not tracked as part of the model integration, for example, because of the lack of dissipative heating of the turbulent kinetic energy (TKE; e.g., Fiedler 2000), or neglecting the radiative impact of precipitating hydrometeors (Waliser et al. 2011). Sun et al. (2010), Huang et al. (2007), and Hu et al. (2008) have pointed out that CFS has low cloud cover; this may be one of the possible reasons for the top-of-the-atmosphere energy imbalance in ESMv1. Within this context, it is worth noting that the annual average absorbed shortwave and outgoing

![Fig. 10. Time series of wavelet power spectra of the gravest principal component from the EOF analysis of the North Pacific SST (20°–60°N, 120°E–120°W; see Fig. 9) for (a) HadISST, (b) ESMv1, and (c) CFSv2. The black contour is the 10% significance level. (d)–(f) The corresponding time-averaged spectra. The dashed line shows the 10% significance for the time-averaged power spectra.](image-url)
longwave radiation values across the ITCZ regions for the ensemble average of CMIP3 GCMs were shown to have biases, as reported by Trenberth and Fasullo (2010). Trenberth and Fasullo (2010) also find that many of the CMIP3 models poorly simulate the energy budget in the Southern Hemisphere. This aspect needs further attention. Importantly, a recent study by Bombardi et al. (2015) shows that, despite such biases, retrospective decadal forecasts by the CFSv2 model show high predictive skill over the Indian, the western Pacific, and the Atlantic Oceans. Another issue that needs further attention is that despite an improvement in the oceanic precipitation, the dry bias over the Indian subcontinent associated with the CFSv2 simulations is still seen in the ESMv1 simulations as well. These issues will be addressed in the next version of the model. Significantly, a few recent sensitivity experiments carried out using the CFSv2 model (Hazra et al. 2015) suggest that improving the cloud microphysics will alleviate this problem substantially. In addition, parallel efforts are also working toward including an aerosol module in the ESM.

Summing up, the ESMv1 is a promising development for facilitating future projections relevant to South Asian climate, specifically those that envisage the next three to five decades in the future.

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**CLIMATE CHANGE/POLICY**

“This book is timely because global climate change policy is a mess.... Drawing on concrete examples and a broad range of social science theory, this book convincingly makes the case for a social learning approach to both adaptation and emissions mitigation.”

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**Adaptive Governance and Climate Change**

RONALD D. BRUNNER AND AMANDA H. LYNCH

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

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


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Through a series of reviews by invited experts, this monograph pays tribute to Richard Reed’s remarkable contributions to meteorology and his leadership in the science community over the past 50 years. 2003. Meteorological Monograph Series, Volume 53; 139 pages, hardbound; ISBN 1-878220-58-6; AMS Code MM53. List price: $80.00 AMS Member price: $60.00

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Cloud computing activities are rapidly expanding within the public and private sectors and provide new capabilities for supporting numerical weather prediction and other applications.

Recently, cloud computing has assumed a greater role in the daily lives of many scientists and engineers, following alongside the growing capabilities of smartphones, other mobile devices, and workstations. Cloud computing has improved the efficiency of data storage, delivery, and dissemination across multiple platforms and applications, allowing easier collaboration and data sharing throughout the scientific community. In our personal lives, cloud computing supports the widespread availability and distribution of audio and video content, such as streaming music and movies available through a growing number of commercial providers. Cloud resources serve as the backbone to countless web pages and web-driven applications used by the general public, including data processing and distribution systems that disseminate key weather forecasting, severe weather warning, and climate information. This article reviews basic definitions of cloud computing terminology and describes cloud-based regional weather forecast modeling and spinoff applications to support capacity-building activities in developing countries.

Although the phrase “in the cloud” is commonplace in advertising for new software applications, formal methods have been established for defining cloud resources and their applications. The National Institute of Standards and Technology (NIST; Mell and Grance 2011) defined cloud computing as “a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g. networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.” The NIST identified the essential characteristics of cloud computing, which include capabilities that can be requested automatically through traditional platforms such as mobile phones or desktop...
workstations, the sharing of and access to pooled resources regardless of geographic proximity, rapid scalability of those resources to match end-user demand, and metered usage that ensures transparent cost accounting for resources used in a given application. Cloud environments are further subcategorized based upon their intended use and availability. Private clouds are those used and maintained by a single organization, whereas public clouds are available to the general public and maintained by another entity. Private and public clouds operate under three primary service models. Software as a service (SaaS) provides software capabilities, primarily through web-based interfaces, with management of necessary computing resources supported by the cloud provider. Often, SaaS applications are provided on a pay-per-use system, such as web-based teleconferencing (e.g., GoToMeeting) and database or customer management applications (e.g., Salesforce). Platform as a service (PaaS) provides a maintained software and networking platform where paying users can build and refine their applications (e.g., Google’s App Engine). Infrastructure as a service (IaaS), the focus of applications described in this article, provides basic computing hardware and storage, as well as an operating system, through a series of virtual machines (VMs) that the user can manipulate to execute their desired tasks.

The availability of IaaS within public and private clouds permits a wide variety of hardware configurations and storage options to support numerous applications. For example, the Amazon Elastic Compute Cloud (EC2) offers VMs with predetermined configurations of operating systems, and computing and storage resources. These resources can be allocated from physical hardware located in several domestic and international locations, ranging from the east (northern Virginia) or west (Oregon and Northern California) coasts of the United States to the European Union (Iceland), South America (São Paulo, Brazil), and Asia (Singapore; Tokyo, Japan; and Sydney, Australia). VMs on EC2 range from “micro” configurations comprising a small number of CPUs and storage options to “extra large” configurations with as many as 32 CPUs and terabytes of disk space. VM options are also targeted to specific applications by offering cluster compute, memory, or storage-optimized options, or the recent addition of VMs powered by graphical processing units. When created, a VM can be assigned one of several operating systems, and the resulting system is referred to as an instance. Costs for instances are billed at an hourly rate corresponding to the class of the underlying VM and generally scale with increases in computing resources. While up and running, VMs are charged an hourly rate; therefore, their timely spinup, use, and termination must be carefully managed to minimize cost. Termination of a VM leads to the loss of all data, unless results are first moved to a more permanent cloud storage service. Other options for pausing and resuming an instance are available, depending upon the instance configuration. Changes made to the EC2 instance and VM configuration can be preserved and cloned through use of a machine image. In the EC2 environment, Amazon Machine Images (AMIs) produce a snapshot of the VM software configuration and allow for later restoration by incorporating a saved image into a fresh VM. The same AMI can be launched onto multiple VMs to clone a given configuration, allowing for rapid scalability of an application.

To support data-intensive applications, the Amazon Simple Storage Service (S3) provides large-capacity object storage for datasets, as needed, subject to an additional, monthly billing rate. Storage space on S3 can be used to create data objects that are accessible by VMs through network transfers rather than mounted volume storage, allowing for the push or pull of data to associated VMs. Increased availability of cloud-based storage solutions such as S3, collocated processing of data by VMs, and sharing of computing configurations via AMIs may offer new opportunities for scientists to share access to and processing of large data volumes, reducing the need for the push–pull of content used in collaborative research. Whereas disks in the VM are lost upon termination, data pushed to S3 or configurations stored as an AMI allow for persistence. Since both the storage of AMIs and the usage of S3 are typically cheaper than uptime costs of a VM, their combined usage allows users to retain their progress without paying for the indefinite uptime of a VM.

The performance of the EC2 environment has been compared to more traditional high performance computing (HPC) systems by Jackson et al. (2010). Some limitations within the EC2 environment at that time included varying latency among compute instances of unknown proximity, unknown competition of multiple users operating VMs on the same hardware, variability in hardware assigned to each virtual machine, and occasional outages of various EC2 components. Recently, the EC2 environment has added cluster compute instances that address some of these concerns by improving network efficiency and hardware homogeneity for high performance computing applications.

Cloud-based support for IaaS naturally aligns with concepts of high performance computing that are used within the meteorological community and, specifically, numerical weather prediction (NWP).
High performance computing systems supporting NWP are typically composed of a head node that manages the model source code, and execution of the code across a larger number of computing nodes. In traditional applications, these nodes are composed of physical hardware with a static configuration, but similar systems can be configured in a cloud environment. For example, VMs can be used to construct a head node and supporting compute nodes by managing their configurations through the development and maintenance of machine images. The entire system can be launched through a series of scripts that commission the appropriate VMs, establish necessary network configurations, and prepare the system for the execution of a given application. Herein, this study focuses on the application of VMs, AMIs, and cluster compute instances to provide a regional modeling framework in scenarios where access to larger HPC resources is limited.

**IAAS IN SUPPORT OF CLOUD-BASED NUMERICAL WEATHER PREDICTION.**

Researchers at the National Aeronautics and Space Administration’s (NASA’s) Marshall Space Flight Center and Ames Research Center (ARC) collaborated on the use of the Weather Research and Forecasting (WRF) Model within private and public cloud environments. The team obtained the then-latest version of the National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS) Science and Training Resource Center (STRC) Environmental Modeling System (EMS; Rozumalski 2014), which comprises a set of data download and processing scripts alongside precompiled binaries of the WRF Model. The STRC-EMS also includes automatic subsetting of larger-domain NWP fields to reduce the amount of data required for download, and options to include unique, higher-resolution land surface and sea surface initial conditions provided by NASA’s Short-term Prediction Research and Transition (SPoRT) Center (Jedlovec 2013). The STRC-EMS was first used to explore and understand the feasibility of near-real-time numerical weather prediction within a NASA private cloud environment hosted at ARC. The use of a private cloud initially served as a software development “sandbox,” where the team experimented with varying configurations of VMs to understand model scalability and runtime efficiency, identify networking bottlenecks, and develop scripting capabilities to deploy a near-real-time modeling system. These exercises aligned with the internal goals of the ARC team by supporting a cloud computing initiative led by the NASA Office of the Chief Information Officer.

Outcomes included benchmarks of performance in public and private cloud environments and a broader understanding of science user requirements for cloud access and utilization. As a result, the team developed a fully scripted capability that allowed for the launch of an STRC-EMS modeling system, including execution of a modeling domain, postprocessing of the resulting simulation, and dissemination of the data to a specific end user.

Once established, the scripted system was transitioned to the Amazon EC2 environment. Scripting included options to allow for the selection of the EC2 geographic region and the assignment of VM types for the file system and compute instances. Administration of the system is performed through a free “tiny” instance currently provided to all EC2 accounts. At a predetermined time each day, the administrative instance executes a script that constructs the modeling system by provisioning the necessary cluster compute VMs, applies the necessary AMIs, and establishes the required networking environment (Fig. 1). Once this is complete, specifics of the model domain and configuration are obtained from the Amazon S3, as the configuration for a given region is static and must be retained after computing VMs are terminated. Once the domain is in place, automated STRC-EMS scripts obtain the necessary initial and boundary conditions by subsetting them from the National Centers for Environmental Prediction (NCEP)/Environmental Modeling Center’s (EMC’s) Global Forecast System, along with higher-resolution sea surface temperatures provided by the NASA SPoRT Center. In total, this represents around 20 MB of data acquired from external Internet sources, but inbound data transfers were not charged to EC2 users at the time of this study. STRC-EMS scripts perform the necessary preprocessing, initialization of larger-scale simulation data, execution of the WRF Model, and postprocessing to predefined gridded binary (GRIB) output fields and desired vertical coordinates. Postprocessed GRIB outputs are pushed to the end user via FTP for further use and distribution by the recipient. Outbound data volumes are highly customizable within the WRF-EMS and user costs depend upon the total monthly volume of data transferred out of the EC2 environment. Data transfer speeds depend upon the network performance between EC2 and the end user. In environments where bandwidth is limited, forecast output and decision aids could be produced in a graphical format, such as hosting a website or web-mapping service using additional EC2-based resources. Once the data have arrived, the end user can incorporate the output within their decision support system or use...
the data to drive additional applications. When the postprocessing and data dissemination processes have completed, the script terminates the model simulation and decommissions all VMs composing the head and compute instances, ending VM charges against the EC2 user account. Then, with the administration node still intact, the system waits patiently until the next forecast period.

COST AND PERFORMANCE METRICS. A fundamental difference between IaaS and the use of traditional (noncloud) resources is the cost model within the EC2 or other cloud environments. Local systems are purchased at a fixed, known cost, followed by costs for administrative support and utilities needed to provide power and cooling. This often occurs as a large upfront cost for a hardware purchase, followed by smaller, longer-term, and incremental costs for depreciation, maintenance, and upgrades. In the cloud environment, each component shown in Fig. 1 represents a metered resource, similar to a household utility. For example, VMs are charged at an hourly rate, and storage on S3 is charged at a rate based upon total monthly usage. Other charges are incurred for certain types of network support, storage of AMIs, and in- or outbound data transfers. VMs include additional cost options based upon usage that is on demand and charged immediately upon usage, or other options for larger, upfront purchases of compute time. Herein, discussions focus on costs associated with on-demand usage, but Amazon EC2 describes additional cost models and their perceived advantages on their pricing web page (Amazon Web Services 2014).

Since the costs of a cloud-deployed system depend heavily upon the time period when the system is active, optimizing the system requires trade-offs between acceptable data latency, data delivery, model resolution, complexity of simulated processes, and cost. Current pricing models charge a full hourly rate for any fractional hour of CPU time that is used; therefore, even small increases in performance efficiency that reduce fractional hour usage can produce significant cost savings. To understand system performance, short-term (6 h) model simulations were executed in
the Amazon EC2 West (Oregon) region over a varying number of compute instances and during different times of day. Characteristics of the model simulation are listed in Table 1 with domain coverage shown in Fig. 2. This configuration represents a plausible, regional configuration supporting multiple nested domains with cloud-permitting resolutions that employ all scales of physical parameterizations (e.g., cumulus to single-moment bulk microphysics, land surface, boundary layer, and radiation) available within the STRC-EMS. A 6-h integration period was selected to include an appropriate model spinup time. In this interval, processing time and memory requirements for precipitation and other parameterized processes are fully engaged, resulting in a consistent number of real-time minutes that elapse between each hour of forecast output. For example, when performance stabilizes to produce an hour of forecast output every \( N \) minutes, the CPU time for a longer forecast can be reasonably estimated by multiplying the number of minutes per forecast hour by \( N \) minutes, converting to hours, and rounding any fractional hour to a full hour.

The demonstration case using a single-model configuration represents a deterministic approach, which may offer limited predictability for some synoptic or mesoscale events (e.g., severe weather, split flow aloft, cutoff lows, or blocking highs) versus multimodel ensembles that better characterize forecast uncertainty. If a regional simulation is not perceived as being valuable for an expected event, cloud-based simulations could be disabled to reduce user cost. Where ensemble approaches are desired, organizations could make use of multiple cloud-based forecast instances to generate an ensemble of simulations with varying initial and boundary conditions, physics configurations, or perturbations, and perform any necessary postprocessing after results are available. Each ensemble member would result in varied performance metrics due to differences in parameterization requirements and processing speeds, and additional costs incurred for any postprocessing performed with cloud resources. Since VM costs are based upon hourly rates, costs should scale with expected differences in runtime performance: schemes that require an additional 10% of runtime would add an additional 10% in cost, and so on. Cloud-based use of ensembles is plausible, but a thorough analysis of cost and performance among the full range of WRF physics packages was beyond the scope of this study.

Given the stable performance in a 6-h period and fixed hourly rates in the on-demand pricing model, VM costs were estimated by scaling runtime to a 48-h simulation. VM costs of a single simulation ranged from around $40 to $75 across the system configurations examined (Fig. 3). Billing information for testing and development indicated that VM usage composed more than 95% of simulation costs. To determine configuration efficiency, runtime performance was assessed by dividing the time required to perform the simulation by the hours simulated. Using this metric, efficiency ranged from 7% to 13% of real time (lower is better), which required 3–6.3 wall-clock hours to complete a 48-h simulation, depending upon VM usage.

The range in configuration and cost allows an end user to select an appropriate level of computational efficiency that meets data delivery and cost goals. However, it is important to note the diminishing marginal utility that occurred when simulations were executed with more than eight cluster compute instances (128 virtual CPUs). In other words, further increases in the number of compute instances (VMs) did not translate into increased performance and cost efficiency for the tests conducted on the Amazon EC2. Limits on internal network performance are believed responsible for this deficiency, consistent

<table>
<thead>
<tr>
<th>Table 1. Characteristics of the STRC-EMS simulations used in performance testing.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal grid spacing: D01, 12 km; D02/D03, 4 km</td>
</tr>
<tr>
<td>Initial and boundary conditions: NCEP/EMC Global Forecast System forecasts (Moorthi et al. 2001; Han and Pan 2011)</td>
</tr>
<tr>
<td>Cumulus parameterization: Kain–Fritsch; D01 only (Kain 2004; Kain and Fritsch 1990, 1993)</td>
</tr>
<tr>
<td>Short- and longwave radiation: Rapid Radiative Transfer Model for GCMs (RRTMG) (Mlawer et al. 1997)</td>
</tr>
<tr>
<td>Land surface model: Noah (Ek et al. 2003; Chen and Dudhia 2001)</td>
</tr>
<tr>
<td>Bulk microphysics: WRF single-moment 6-class (Hong et al. 1998; Skamarock et al. 2008)</td>
</tr>
<tr>
<td>Sea surface temperature: 2-km NASA SPoRT SST composites (Haines et al. 2007; LaCasse et al. 2008; Case et al. 2011; Case et al. 2012)</td>
</tr>
<tr>
<td>Amazon virtual machines: c3.4xlarge: 16 vCPU, 30 GB of RAM, and 2 × 160 GB solid-state disk drives per virtual machine operating on Ubuntu Linux</td>
</tr>
</tbody>
</table>
with scalability issues identified by Jackson et al. (2010). Whereas high performance computing systems operate with high-speed internal networks (e.g., Infiniband) and are fully optimized to support multiprocessing applications, the EC2 environment used in these experiments did not support higher-speed networking capabilities. Internal networking limitations appear to degrade model performance beyond an eight-node configuration and, to a lesser extent, input–output processes of writing model results to disk. However, an eight-node configuration provides the highest runtime efficiency available among the tested configurations, cutting simulation runtime by more than half compared to a two-node run, with a commensurate increase in cost. EC2 and other providers are constantly improving network access and improved performance is expected for future tests and applications.

**IAAS IN SUPPORT OF CAPACITY BUILDING AND REGIONAL FORECASTING APPLICATIONS.** Cloud computing can offer additional resources to support regional weather forecast modeling, either to support on-demand capacity in response to cloud-generated, regional weather forecasts can support other simulation systems, such as prediction of air quality or dispersion models, weather forecast support during local disasters, or hydrological and empirical models used to predict landslide hazards in areas of complex topography (Kirschbaum et al. 2009).

The NASA SERVIR Project (NASA 2014), a joint effort between the NASA Applied Sciences Program and the U.S. Agency for International Development (USAID), is exploring many of these capabilities. SERVIR provides support for Earth observations and applications to improve environmental decision making within developing countries, focusing on activities relevant to regional hubs around the world. Capacity-building efforts within SERVIR focus on the transition of new capabilities to end users. In this mindset, a simulation system on EC2 can be transitioned to operations over Central America and the Caribbean or other regions of interest by migrating automation scripts and associated machine images to Amazon accounts managed by organizations interested in regional NWP. In this mode, they can establish their own modeling configurations without having to maintain the larger infrastructure and support staff.

![Fig. 2. Domain coverage of the STRC-EMS simulation used in performance testing over Central America and the Caribbean in support of NASA SERVIR. Simulation physics schemes and configuration are shown in Table 1. The dashed red box indicates the geographical window used in model verification for daily simulations during Nov 2013 on domain D01.](image-url)
that would be required for a full-fledged HPC facility. Cloud computing allows for continuity of operations during a disaster by leveraging compute resources that are geographically distant from the affected area. In turn, multiple EC2 host regions allow for options to continue model execution during periods when disasters may affect the operation of cloud resources in a given area. By operating in a cloud environment, modeling resources are far removed from the impacted area and can continue unaffected. Finally, as SERVIR interests expand, other EC2 regions can be incorporated to support local NWP efforts and spinoff applications. For example, EC2 regions in Europe and Asia can be leveraged to support partnering, regional hubs that are in closer proximity to cloud resources to reduce latency while maintaining forecasting capabilities. These hubs can continue to assume responsibility for operating simulations in a cloud environment, supporting their local decision making at costs that are reduced in comparison to establishing, maintaining, and staffing a high performance computing facility.

REGIONAL MODELING AND VERIFICATION OVER CENTRAL AMERICA AND THE CARIBBEAN. SERVIR previously established a regional hub and partnerships within Central America. In support of SERVIR activities, the NASA Ames and Marshall team established a regional modeling application using IaaS concepts in private (NASA OpenStack) and public (Amazon EC2) cloud computing environments (Fig. 1). The system has been running in real time over Central America and the Caribbean since 2013 using the configuration and domain summarized in Table 1 and Fig. 2. The WRF Model is initialized once daily at 0600 UTC and run for 48 h. The selection of the nonsynoptic time of 0600 UTC was based upon expected model runtime and desired delivery of outputs to support decision-making activities, but can be changed easily by the user for other applications. This cloud-hosted simulation provides guidance to SERVIR end users in Central America and the Caribbean, and can be used for a variety of applications, such as assessing heavy rainfall and landslide threats, air quality modeling, and resolving strong mountain gap winds.

As an example of such an application, an NWP simulation of a mountain gap wind event is shown in Fig. 4. These strong gap winds, known regionally as tehuantepecers (e.g., Schultz et al. 1997), occur in the Chivela Pass and the Gulf of Tehuantepec when a cold front and attendant, broad region of high pressure move across the area (Fig. 4a). Tehuantepecers pose a significant threat to marine interests in the Gulf of Tehuantepec as shown by forecasts from the Tropical Analysis and Forecasting Branch (TAFB; Fig. 4b), but more readily available, coarser global models may underestimate their intensity. In this example, cloud-hosted, regional NWP simulations provided a reasonable depiction of the strongest gap winds (Fig. 4c) when compared to wind speeds estimated by the WindSat instrument aboard the Coriolis satellite (Fig. 4d). Accurate representation is key, as these gap wind events can reach hurricane-force strength in some extreme situations.

Regional model guidance is only valuable for local forecasting and spinoff applications if it consistently reproduces the observed weather. Quantitative model verification statistics were also provided to SERVIR

![Fig. 3. Summary of runtime performance and estimated VM costs for simulations using a varying number of compute instances (c3.4xlarge, $1.20 h^{-1}), in addition to a single head node, and assumed 1 h required for postprocessing and data distribution.](image-url)
so that decision makers can understand the quality of these WRF forecasts. Outside of the cloud environment, automated verification scripts are provided by the NASA SPoRT team (Zavodsky et al. 2014) for execution of the NCAR Model Evaluation Tools (MET; Brown et al. 2009). Model error statistics were generated over the WRF Model domains shown in Fig. 2 using point observations available in the NCEP Global Data Assimilation System. Model precipitation skill scores are produced using quantitative precipitation estimates from the NCEP Climate Prediction Center morphing technique product (CMORPH; Joyce et al. 2004). Figure 5 summarizes error statistics on WRF Model domain D01 during November 2013 calculated in the verification region shown in Fig. 2. Results demonstrate the skill that can be achieved by utilizing cloud computing resources in combination with other modeling and postprocessing tools. During this period, the WRF Model exhibited a slight cool, moist bias throughout the daily 48-h forecasts, particularly during the afternoon and early nighttime hours (forecast hours 12–24 and 36–48; Figs. 5a,b). A consistent high wind speed bias of about 1–2 m s$^{-1}$ during November 2013 occurred in the WRF Model configuration (Fig. 5c) during most forecast hours. Forecasters can use this information of systematic bias to modify their

Fig. 4. (a) Topography in eastern Mexico and a common synoptic regime resulting in strong gap winds in the Gulf of Tehuantepec. (b) NCEP TAFB graphicast valid 28 Nov 2013. (c) Depiction of the tehuantepecer high-wind event from 28 Nov via a 30-h WRF-in-a-cloud forecast of 10-m winds valid 1200 UTC 28 Nov. (d) WindSat-derived wind vectors valid 1240 UTC 28 Nov.
Fig. 5. Composite verification statistics for Nov 2013 as a function of forecast hour on D01, for the subdomain depicted by the red box in Fig. 2. Statistics shown include the mean error (ME), error standard deviation (ESTDEV), and root-mean-square error (RMSE) for (a) 2-m temperature, (b) 2-m dewpoint temperature, and (c) 10-m wind speed. (d) HSSs of 3-h accumulated precipitation for 5-, 10-, and 25-mm accumulation thresholds.
Furthermore, the on-demand nature of cloud computing allows for simulations to be requested in response to significant events or local disasters if the end-user community cannot afford daily simulations. Cloud computing and IaaS-driven applications will provide new opportunities for establishing data processing and simulation capabilities within end-user communities that do not have immediate access to a fully established supercomputing facility.

**ACKNOWLEDGMENTS.** The authors thank Karen Petraska of the NASA Office of the Chief Information Officer for her support in fostering the collaboration involving her office, NASA Ames, and NASA Marshall targeted at leveraging the Amazon EC2 environment as well as Tsengdar Lee, High End Computing Program manager at NASA Headquarters, for support to the SPoRT and SERVIR teams fostering experiments in operating NWP models in private and public cloud environments. The authors thank three anonymous reviewers for their comments and guidance that improved the final manuscript. The use or mention of a specific commercial product within this study does not represent an official endorsement by the authors or their affiliated organizations.

**REFERENCES**


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THE NCAR ADVANCED STUDY PROGRAM SUMMER COLLOQUIUM: CARBON–CLIMATE CONNECTIONS IN THE EARTH SYSTEM

What: Twenty-five graduate students and 60 scientists working on the terrestrial and ocean sides of the carbon cycle met to explore research challenges common to both communities.

When: 29 July–16 August 2013

Where: Boulder, Colorado

The 2013 colloquium was supported by NCAR ASP through funding from the National Science Foundation.
climate state, and future warming will likely reduce their uptake rates. Furthermore, both sinks depend, at least in part, on the concentration of CO₂ in the atmosphere. However, many uncertainties remain regarding the mechanisms that regulate these natural carbon sinks and feedbacks, which are not easily quantifiable. Achieving a better understanding of those processes is essential to climate prediction and to uncertainty quantification. Earth system models provide a coherent framework in which to represent the mechanisms regulating carbon sinks and their interaction with climate. Ultimately, improving these models will yield more reliable predictions of future climate evolution.

The 2013 colloquium included a researcher workshop during the second week titled “Key Uncertainties in the Global Carbon Cycle: Perspectives across Terrestrial and Ocean Ecosystems.” The objectives of the workshop included identifying important, cross-cutting problems in carbon–cycle science common to land and ocean communities. In our opinion one of the major successes of the colloquium was that it provided a unique, and truly interdisciplinary, learning experience for the majority of participants: students, lecturers, and researchers. Here we delve into the lessons learned from this event.

**ASP STUDENT ACTIVITIES.** The students who took part in the colloquium (names and affiliations are provided in the online supplement: [http://dx.doi.org/10.1175/BAMS-D-13-00246.2](http://dx.doi.org/10.1175/BAMS-D-13-00246.2)) were selected from over 120 applicants who had completed at least one year of graduate studies in programs in the United States, Canada, Europe, Asia, and Africa. Half of the students had primary research interests focused on the terrestrial biosphere and the other half on the ocean. The colloquium lecture component introduced the physical, biological, and chemical mechanisms that regulate the global carbon cycle and their representation in Earth system models. The students also participated in hands-on, computer-based tutorials covering Earth system modeling and analytical techniques relevant to carbon cycle science.

Student projects constituted a major component of the colloquium. Groups of four or five students worked to examine aspects of cutting-edge Earth system simulations submitted to phase 5 of the Coupled Model Intercomparison Project (CMIP5) and available through the NCAR computer facilities. Projects were supervised by the lecturers and NCAR scientists, and they covered a range of pressing problems, from developing new metrics to assess the climate model outputs to examining the role of nutrient limitation in the projected terrestrial carbon sink or in the equatorial Pacific Ocean.

**THE WORKSHOP.** The middle week of the ASP colloquium (6–10 August 2013) consisted of a workshop focused on key uncertainties in global carbon cycle modeling. The workshop brought together 60 terrestrial and ocean carbon cycle scientists from around the world to explore key uncertainties in the global carbon cycle. Its aim was to generate a conversation across traditional disciplinary boundaries to highlight the conceptual challenges common to the two communities while simultaneously introducing the next generation of scientists to the frontier of research. Specifically, the workshop focused on five main topics: global carbon cycle controls, mechanisms that regulate nutrient cycling and their impacts, remineralization pathways, the role of individuals in ecosystem dynamics, and observational data that might constrain carbon cycle feedbacks. Speakers and titles of their presentations are in the online supplement ([http://dx.doi.org/10.1175/BAMS-D-13-00246.2](http://dx.doi.org/10.1175/BAMS-D-13-00246.2)).

A round table discussion highlighted if and how research questions with common goals had the potential to be successfully addressed using similar approaches by the two communities. For example, the quantification of the role of extreme but infrequent events in the carbon budget could benefit from parameterizing higher-order statistics in both the terrestrial and the ocean components. Innovative approaches on how to model carbon losses to the atmosphere in terrestrial ecosystems through fire or storms and carbon export to the deep ocean by large sinking particles have the potential to be shared between ocean and land researchers. On the other hand, improvements in the representation of nutrient limitation must follow different trajectories in the two communities due to differences in the relative importance of biological versus physical processes governing the spatial and temporal variability of nutrient cycling.

The workshop identified five major modeling challenges common to the scientific communities

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2 The ASP colloquium workshop was supported by the Carbon Cycle Interagency Working Group, the U.S. National Institute of Food and Agriculture, the Ocean Carbon and Biogeochemistry (OCB) program, and the U.S. Climate Variability and Predictability Program (U.S. CLIVAR).
working on the terrestrial and ocean sides of the carbon cycle, as summarized below.

1) **Remineralization/decomposition.** Microbial respiration is common to land and ocean systems. On land, microbial respiration converts organic carbon and nutrients back to inorganic forms, with a loss of carbon from terrestrial soils and a return of nutrients to bioavailable pools as end results. In the ocean, microbial respiration of sinking organic matter controls the depth of remineralization, which in turn determines the longevity of the carbon sequestration. The dependence of respiration rates on environmental conditions, however, is poorly understood in both systems. Given that the underlying reactions are similar on land and in the ocean, we expect similar responses to changes in analogous environmental variables. The colloquium explored how to circumvent barriers of language, framing of questions, and channeling funding streams in order to develop a transdisciplinary initiative between terrestrial and ocean scientists studying respiration pathways.

2) **Nutrient limitation.** The representation of nutrient limitation in coupled carbon–climate models has followed different paths across the land and ocean communities. In land models, accounting for nutrient limitation is a relatively new challenge and a leading-order source of uncertainty when projecting into the future the terrestrial contribution to carbon uptake. Nutrient limitation is a primary constraint in ocean ecosystem models, although the proportion of different essential elements is still crudely treated. The factors that distinguish nutrient limitation in the ocean from its terrestrial counterpart are a fast biomass turnover rate, fairly strong observational constraints on nutrient cycling, and the homogenization of the marine nutrient reservoir by circulation and mixing. Time scales and substrates differ markedly between the land and ocean; nonetheless, many concepts are transferable across the two communities. In particular, the workshop highlighted the common need for more observational studies examining the mechanistic controls on nutrient budgets and for a better synergy between modelers and experimentalists to better constrain model formulations through targeted manipulation experiments.

3) **Ecology and physiology.** Terrestrial and marine ecosystems consist of organisms with physiological capacities and constraints; these “traits” determine functional roles, success in competition for resources that limit their growth, and carbon cycling characteristics. The realism of and potential for reliable predictions by ecosystem models is predicated on the accurate understanding and depiction of the feasible trait space. Traits result from resource allocation in the context of finite resources and physiological capacities; therefore, trait space is characterized by trade-offs. A key requirement to developing robust representations of trait spaces lies in accurately understanding physiological trade-offs and the criteria that organisms employ for optimization. Marine and terrestrial ecosystem models have been developed to represent the evolution of a uniformly "seeded" distribution of organisms with different traits that produces a realistic biogeography following local selection processes. The exploration of those models is in its infancy, but they represent a promising tool for examining carbon–climate feedbacks in more biologically mechanistic ways. The workshop emphasized that research on this topic should involve a tighter collaboration between physiologists and modelers. Optimization of traits at both ecological and evolutionary time scales should be considered.

4) **Disturbances and trophic coupling.** Ecosystem structures can be dramatically altered by episodic, rare events. In nonlinear systems, such as our climate or land and marine ecosystems, a forcing exerted intermittently can yield different outcomes than the same integral forcing applied uniformly in time. Mortality rates, for instance, may vary greatly over time in response to sporadic events. Nonetheless, ecosystem models usually represent mortality as a constant loss (in time) proportional to the population density. We need to better understand and quantify the ecosystem responses to disturbances; we also need novel approaches to model processes highly susceptible to disturbance events, like mortality, especially for terrestrial ecosystems given the long response time scales associated with perturbations. Another important source of uncertainty identified at the workshop is provided by the representation of trophic coupling. In marine ecosystems, trophic coupling exerts an important control on phytoplankton biomass and export. Models parameterize such coupling in a rudimentary way and behave dramatically different for subtle parameter changes. We think that improved data constraints for grazing
parameterizations in the ocean through a targeted observational effort should constitute a first-order priority.

5) Physical climate setting. In the Earth system modeling framework, carbon cycle models are embedded in global climate models that provide the physical setting. Since many ecosystem processes are sensitive to physical climate variables, it is difficult to attribute specific features of model behavior to a particular component, quantify feedbacks, or disentangle errors and biases. Ecosystem models should therefore be evaluated using suites of different physical settings—to provide better insight into the representation of ecological and physical processes—and climate–carbon feedbacks. There is a clear need for modeling frameworks that permit interoperability of subcomponents. We are not recommending a common coupling infrastructure (e.g., the ability to run an ocean model with different atmospheres), but rather modularity that permits swapping process-level parameterizations. Additionally, it is currently unclear how nonlinear ecosystem responses to physical “disturbances” may alter large-scale carbon distributions. The potential for them to impact the carbon cycle requires that extremes over land (e.g., fires, hurricanes, droughts and floods, heat waves and cold spells) and mesoscale eddies in the ocean are resolved in coupled climate models.

SUMMARY. The organization of such a transdisciplinary colloquium and workshop presented unique challenges. A great deal of effort was spent ensuring that lectures and talks were cohesive and that all speakers identified ways in which their perspective on carbon–climate interactions transcended traditional terrestrial and ocean disciplinary boundaries. By far the best part of the colloquium was the interaction with the strong group of students. A sense of deep curiosity and enthusiasm permeated the event, and personal and professional relationships developed at the colloquium continue to blossom. By exposing students to intense, transdisciplinary training, we hope to have stimulated new ideas that will assist them in the development of cross-disciplinary cooperative research efforts.

The success of this colloquium clearly calls for sustained activities, such as the ASP summer initiatives, to coordinate cross-disciplinary research.

ACKNOWLEDGMENTS. The ASP summer colloquium is generously funded by the National Science Foundation. The workshop was made possible through support from the Carbon Cycle Interagency Working Group, the U.S. National Institute of Food and Agriculture (Grant 11362158), the Ocean Carbon and Biogeochemistry (OCB) program, and U.S. CLIVAR. We wish to thank all the NCAR researchers who contributed to the success of the activity.

REFERENCES

Increasing Access to Research through Participation in CHORUS

A key aspect of the AMS mission is making scientific results widely available. That philosophy drove the Society almost two decades ago to post online as part of a searchable database all the peer-reviewed scientific articles it has ever published, and to make any article more than two years old freely available to all. It also explains why most of the presentations made at AMS scientific conferences over the past decade or so are freely available online. AMS has demonstrated a longstanding commitment to broad dissemination of research results.

In 2013, the White House Office of Science and Technology Policy (OSTP) issued the memorandum, “Increasing Access to the Results of Federally Funded Scientific Research,” which requires each major federal funding agency to have a plan to make research results funded by that agency freely available to the public. This includes published journal articles coming from federally funded research, which must be made open-access after a postpublication embargo period of no longer than 12 months.

In response to the OSTP memo, a group of major scholarly publishers (both for profit and nonprofit) organized the Clearinghouse for the Open Research of the United States (CHORUS; see www.chorusaccess.org/) as a way to provide compliance for the agencies. CHORUS is designed to leverage the infrastructure already in place within the scholarly publishing community to track papers coming from federal grants and contracts, make the metadata on those papers (including the DOIs of the published papers) available to the federal agencies, and ensure that the paper is easily discoverable and publicly available after the prescribed embargo period and in perpetuity. CHORUS also provides freely available dashboards with real-time reporting on the public accessibility and funding agency compliance for the publishers’ content.

AMS was an early signatory on the CHORUS project and recently became a member of CHOR, the nonprofit organization that is managing CHORUS. Becoming a CHORUS participant is fully consistent with the Society’s commitment to making research results widely available, while also ensuring that it is the authors’ published version of record that is made available through all outlets.

AMS will implement the CHORUS protocols over the coming months. For instance, we will collect funder information from authors submitting to AMS journals, taking advantage of the FundRef registry that has been created to coordinate the catalog of funding agencies and ensure that research coming from funded projects can be correctly tracked and linked. For some funding agencies, CHORUS will represent the primary path to compliance with the OSTP mandate, eliminating the need for additional action by the author or the author’s institution. For other funding agencies, CHORUS will augment the agency’s compliance procedure. The result is increased discoverability for the author’s research, increased accountability for the funding agency, and increased accessibility to research results for the entire community. AMS is proud to be part of this important initiative.

Keith Seitter, CCM
AMS Executive Director
**About Our Members**

**Baron Services** of Huntsville, Alabama, recently received a $1.38 million contract from the U.S. Army Corps of Engineers to enhance weather radar capabilities for the U.S. Army Cold Regions Test Center with operations at Fort Wainwright’s Donnelly Training Area near Fort Greely, located 100 miles from Fairbanks, Alaska. Baron’s X-Band Dual Polarization radar system will provide enhanced knowledge of weather patterns that could adversely impact operations at the site in the snow, extreme cold, and subarctic natural environment. The new radar systems will help the center supply timely, accurate, and relevant information to the army, sister services, the Department of Defense, the U.S. government, and international and commercial customers. The expected project completion date is October 2015.

**Josh Johnson** has been promoted to the position of chief meteorologist at WSFA-12 in Alabama. For the past seven years, Josh has served WSFA-12 News as the meteorologist on the WSFA-12 News morning show *Today in Alabama*. Josh is a member of the National Weather Association and serves on their Weather and Forecasting Committee. He graduated from Mississippi State University with a B.S. in geosciences with a concentration in broadcast meteorology, and earned the AMS Seal of Approval in 2007.

**AccuWeather Inc.** has been recognized with a Governor’s ImPAct Award, a result of the company’s global leadership, expansive reach, and continued growth. The award is in the Export Impact category in recognition of AccuWeather as “a company that has significantly increased its export sales” and consequently brought outside revenue and new jobs to Pennsylvania.

The Governor’s ImPAct Awards is a signature awards program celebrating companies that have had a substantial impact on the state of Pennsylvania and contributed to job creation and job retention. These companies have proven that they are committed to the state of Pennsylvania, and see the value and benefits of doing business there. AccuWeather and companies from across the state were invited to Hershey, Pennsylvania, to attend the awards ceremony luncheon this spring.

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**On-Air Meteorology**

**10 Questions with . . .**

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

**Alan Sealls**

**WKRG-TV, Mobile, Alabama**

*What inspired you to go into broadcasting?* With a fascination for weather and a talent for performing, broadcasting seemed like a natural combination of my interests. I knew that if I could have a job where everyone needed what I had, and most people couldn’t do the job, I would always have a job!

*In one word, what do you most attribute to your success?* Parents.

*What’s been your most difficult moment on air?* Working the day of 9/11. I’m from suburban New York City, so the senseless loss of life and destruction of property on that day was personal to me. I was angry and sad and that made it hard to be positive and smile, but that’s what’s required of my job.

*How would you define the value of the AMS Seal programs?* The Seal programs have tremendous value in setting standards for knowledge and professionalism. The continuing education associated with the Seals is even more valuable than being granted a Seal.
How has the field changed since you started? The weather broadcaster no longer just does a forecast and presents it on TV. He or she has become a station scientist and a social media multicaster. We are expected to do more, often with less. Many of us have also picked up the duties of computer technicians, web programmers, and graphic artists.

What’s the biggest weather event you’ve reported on? Hurricane Ivan in 2004. I used almost everything I had ever learned as a meteorologist, and I learned a lot in the process.

What weather myths do you hear the most? Chemical trails (chemtrails) are part of a project to harm people; you can only balance an egg on a table on an equinox; weather forecasts are “always” wrong.

What did you learn in school that is most helpful as a broadcast meteorologist? Everything. All the science, communications, art, music, language, history, and economics are interwoven with weather broadcasting.

What technological breakthrough would make your job better? The ability to interrupt a TV program for a tornado warning, only for the people who are in the threat or who want to know about it. After going many months with relatively calm weather, we get so much negative feedback from interrupting a program for a tornado warning where no tornado verifies or where no significant damage occurs.

What music should be the soundtrack for your job? “Everything Must Change.”

Alan Sealls is a former Chair of the Board of Broadcast Meteorology, current Council member, and AMS Fellow. He earned his CBM in 2006. For more information on AMS Certification Programs, go to www.ametsoc.org/amscert/index.html.

COMMUNICATIONS

A NEW WEB VISION

You may have noticed that AMS has recently rolled out a new website, which includes updated content and navigation, as well as a brand new overall design. We hope you like it. This is a critically important step for AMS as we continue making progress on creating an accurate and complete understanding of our value to our members; to the greater weather, water, and climate community; and to society.

The AMS website represents an important mechanism for engaging, exciting, and inspiring people throughout the weather, water, and climate community. Our members and others engaged with AMS all work extremely hard to understand, connect, and share knowledge about science and society. Today, many tens of thousands of people in the private, public, and academic sectors work to ensure that society benefits from that knowledge. We see our website as a very important vehicle in supporting that effort, and a place for the entire community to connect, share, and collaborate.

Our vision for the website moving forward is that it serves the following functions:

1. As a delivery vehicle for the organization’s core assets;
2. As an education portal to inform, educate, and inspire many audiences inside and outside the weather, water, and climate community;
3. As an expression of value to society at large, and
4. As a source of community, bringing together many audiences to share, inform, and collaborate.

We’ll continue adding new content, updates, and information in the coming weeks and months to ensure that the AMS website remains a dynamic, engaging online experience for all audiences. We welcome your feedback and comments at https://www.surveymonkey.com/r/amsredesign.

—Tom Champoux, AMS Director of Communications
Observational meteorological data have been growing in size and complexity. This wealth of data can be used to improve prediction and/or understanding of events, but the amount of data also provides many challenges to processing and learning from it. The challenge of analyzing large data volumes is not unique to meteorology. Computer scientists—and specifically machine learning and data mining researchers—are developing frameworks for analyzing big data for a range of applications. The AMS Committee on Artificial Intelligence and Its Applications to Environmental Science aims to bring AI researchers and environmental scientists together to increase the synergy between the two fields. The AI Committee has sponsored four previous contests on a variety of meteorological problems including wind energy, air pollution, winter hydrometeor classification, and storm classification (Lakshmanan et al. 2010), with the goal of bringing together the two fields of research to discuss a common challenge from multiple perspectives. The winners of the past contests presented in a special session at the AMS Annual Meeting that featured both the results and discussions of the various techniques used, as well as how they could be applied to similar problems. While the discussions had been fruitful and attracted people from different backgrounds, participation in the contests declined from year to year. For the 2013–14 contest, we made significant changes to the contest format in order to increase participation and reach a much wider audience.

Our goal for the 2013–14 contest was to determine which approach produces the best total daily solar energy forecast. We changed three key features of the contest organization. First, we used the year prior to the contest to gather and format a larger and more complex dataset for predictions. Second, we hosted the contest website on Kaggle, a popular platform for AI contests with a worldwide audience. Third, we extended the time window of the contest from just the fall to July through November, and allowed contestants to submit and evaluate entries every day throughout the period. These changes resulted in an order-of-magnitude increase in the number of participants and a broadening of the participant pool from those in the existing meteorological community to scientists and engineers around the world.

DATA. The forecast data used in this study came from the second-generation NCEP Global Ensemble Forecast System (GEFS) reforecast dataset described in Hamill et al (2013). These data consist of an 11-member global ensemble initialized at 0000 UTC every day from 1985 to the present. Forecasts extend to +16 days lead time. The modeling system closely replicates the GEFS as it was implemented in 2012. The initial conditions for most of the dataset used the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) for the control initial condition and the ensemble transform with rescaling (Wei et al. 2008) for generating perturbed initial conditions. Forecast data were archived every 3 h to +72 h lead time, and every 6 h thereafter. More details are available in Hamill et al (2013).

The Oklahoma Mesonet is a permanent mesoscale surface observing network of 120 remote meteorological stations across Oklahoma (Brock et al. 1995; McPherson et al. 2007). The Mesonet represents a partnership of Oklahoma State University and the University of Oklahoma, and is managed by the
Oklahoma Climatological Survey (OCS). Each station measures more than 20 environmental variables, including wind at 2 m and 10 m, air temperature at 1.5 m and 9 m, relative humidity, rainfall, pressure, solar radiation, and soil temperature and moisture at various depths. All sensors are mounted on or near a 10-m tower supported by three guy wires and powered via solar energy.

Downwelling, global solar radiation is measured by the LI-COR LI-200 pyranometer mounted on a boom that extends southward from the tower. Even so, measurements of solar radiation during early morning and late afternoon into the evening may be sensitive to obstructions to the east and west of the station. All solar radiation data are collected and transmitted to a central point every 5 min where (1) sensor-specific calibration coefficients are applied and (2) the data are quality-controlled via automated algorithms and human inspection prior to distribution and archiving (Shafer et al. 2000; McPherson et al. 2007).

The locations of the GEFS and Mesonet stations are shown in Fig. 1. Due to the coarseness of the GEFS grid relative to the Mesonet station spacing, contestants were provided with additional grid points well outside the Oklahoma state boundaries so that any interpolation techniques would not experience any interference from edge conditions.

CONTEST SETUP. The contest was hosted by Kaggle, a company that developed a platform for hosting data mining competitions in addition to providing modeling support for a variety of Fortune 500 companies. For each competition hosted on the site, Kaggle provides pages for describing the competition and the rules, downloading the data, displaying real-time rankings of the participants, and discussions about the contests. The site also automatically manages submission of contestant entries and evaluation of the predictions. The continuous stream of contests on Kaggle has led to the development of a large community of contest participants who come from a wide range of backgrounds and from around the world. For these services and for access to its large user community, Kaggle charges a fee to companies who wish to host their contest through the site, but Kaggle also hosts research competitions for smaller contests organized by academic groups for a small fee. EarthRisk Technologies sponsored the contest and provided the prize money.

For this contest, a small spatial subset of the 11-member ensemble data were extracted over Oklahoma and surrounding regions, consisting of forecasts at the +12-, +15-, +18-, +21-, and +24-h lead times. To be coincident with the observational data, the reforecast data were extracted only back to 1994. These pervaded the forecast training data for the contest’s 1-day solar energy predictions. The forecast variables saved were mean sea level pressure, skin and 2-m temperature, 2-m specific humidity, daily maximum and minimum 2-m temperature, total precipitation in the last 3 h, total column precipitable water, total column integrated condensate, total cloud cover, downward and upward short- and long-wave radiation flux at the surface, and upward long-wave radiation flux at the top of the atmosphere.

The data were split into training, public testing, and private testing sets. The training set time frame extended from 1 January 1994 to 31 December 2007; the public testing set ranged from 1 January 2008 to
31 December 2009, and the private testing set ranged from 1 January 2010 to 30 November 2012. Teams could evaluate their predictions on the public testing set up to 5 times per day and optimize their algorithm based on the evaluation score. The final ranking of the teams was determined from the private testing set results, and the scores were not revealed until the contest concluded. Mean absolute error (MAE) over all stations and days was chosen as the evaluation metric because it does not penalize extreme forecasts as greatly as root mean squared error.

In addition to the contest data, participants also received the results and source code for three benchmark methods that indicated how random selection and interpolation methods would perform on the dataset. The random normal benchmark input random numbers sampled from a normal distribution with a mean of 16 MJ m\(^{-2}\) and a standard deviation of 8 MJ m\(^{-2}\). The other two benchmarks interpolated the GEFS mean total daily incoming solar radiation to the Mesonet sites using nonlinear approaches. One method fit a set of scaled Gaussian mixture models to the GEFS data with an expectation-maximization iterative approach similar to the method of Lakshmanan and Kain (2010). It produced a smoothed field that could be evaluated at any point in the domain and had an MAE of 4.02 MJ m\(^{-2}\). The second approach was to use Catmull-Rom cubic splines to interpolate the nearest four grid points to each Mesonet site. The splines performed significantly better than the Gaussian mixture model approach, with an MAE of 2.61 MJ m\(^{-2}\), although they did have a tendency to have larger extremes than the observed data. Once the spline code was provided to the contestants, 118 of the 160 teams were able to either equal or improve on their performance.

**Gradient Boosted Regression Trees.**

One of the surprising outcomes of the contest was that all of the winning methods made use of the same regression technique, Gradient Boosted Regression Trees (GBRT) (Friedman 2001). GBRT robustly models the (volatile) daily solar energy output from spatiotemporal input variables. For this data, GBRT proved to be an accurate and effective off-the-shelf regression technique because (1) it natively handles data of mixed type, (2) it is robust to outliers (through robust loss functions), and (3) it is nonparametric and has high predictive power.

Mathematically, GBRT is a generalization of boosting (Freund and Schapire 1995) to arbitrary differentiable loss functions \(L\). The method considers additive models of the form

\[
F_m(x) = \sum_{m=1}^{M} \gamma_m h_m(x),
\]

where \(h_m(x)\) are basis functions called weak learners. In GBRT, weak learners are regression trees (Breiman et al. 1984) that are learned sequentially using a forward stagewise procedure. More specifically, at each stage, \(h_m(x)\) is chosen to minimize the loss function \(L\) via steepest descent (using the negative gradient

![Mean Absolute Error by Month](image1)

**Fig. 2.** Monthly MAE and mean error for each of the top four contestants.
of $L$ at the current model $F_m$, while
the step length $\gamma_m$ is chosen using line
search.

**ERROR ANALYSIS.** The top con-
testant methods exhibited similar
monthly error characteristics. The
monthly MAE for all stations (Fig. 2)
follows the average magnitude of solar
energy by month, with the smallest
error in December and January, then
increasing to the highest error in
May and June. All of the contestants
have very similar monthly errors,
with Eustaquio and Titericz (first-
place winners, see sidebar) consis-
tently having the lowest error. The
monthly mean error shows a very small amount of
bias relative to the magnitude of the mean absolute
error. Each contestant follows a similar monthly
trend in the mean error. Eustaquio and Titericz
have a consistently higher mean error than the
other models, which is due to the multiplicative
factor applied to their results.

Analysis of the station error shows the effects of
geospatial distribution on the predictions. For all contestants,
eastern Oklahoma featured generally higher mean
absolute errors compared to western Oklahoma,
with the Oklahoma Panhandle featuring some of
the lowest errors (Fig. 3). This solar error distribu-
tion mirrors the annual precipitation distribution in
Oklahoma. Since the presence of clouds and rain has
a large impact on solar energy amounts, and since
precipitation location and duration are challenging
to predict, this factor is likely a large component of
the increased error in eastern Oklahoma. A subset of
the stations buck the geographical trend, and analysis
of the contest observations shows that some of these
stations recorded extended periods of missing data
that were filled with the mean solar radiation value
for that site. Only a few stations had
these discrepancies, so it did not
have a significant impact on the
overall contest results.

A bootstrap statistical analysis
of the forecast errors was per-
formed on the top four contestants
to determine if there were statisti-
cally significant differences in their
forecasts. The confidence intervals
(Table 1) indicated large amounts of
overlap and no statistically significant differences in
the top four contestants. The scores of the top seven
contestants fall within the confidence interval of the
first place winner, and the top sixteen contestants
fall within the confidence interval of the fourth-
place winner.

**DISCUSSION AND LESSONS LEARNED.**
By hosting the forecasting challenge on Kaggle,
we dramatically increased the participation and
the diversity of the participants from prior years.
This diversity includes a significant increase in
international participation, as well as participation
from people outside of meteorology. This broader
participation was valuable in highlighting meteoro-
logical applications for machine learning and data
mining. However, it also provided some challenges
from the perspective of running a contest with a
final session at an AMS Annual Meeting. Because
the winners were largely international partici-
pants, they were not able to travel to the meeting.
Although most of the winners were able to send a
prerecorded video of their talks and there was an

<table>
<thead>
<tr>
<th>Contestant</th>
<th>95% Confidence Interval (MJ m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Eustaquio and Titericz</td>
<td>(2.028, 2.180)</td>
</tr>
<tr>
<td>2. Lazorthes</td>
<td>(2.044, 2.211)</td>
</tr>
<tr>
<td>3. Zhang</td>
<td>(2.077, 2.224)</td>
</tr>
<tr>
<td>4. Louppe and Prettenhofer</td>
<td>(2.082, 2.244)</td>
</tr>
</tbody>
</table>
informative discussion in the AMS session, future contests could benefit from better use of video technology to engage the winners in discussions in real time.

The data, evaluation system, and results from the contest have broader applicability for meteorologists in the renewable energy forecasting sector. The contest results showcased GBRT, which has not been used extensively in the atmospheric science community to this point. Optimized GBRTs have been shown to provide superior performance on this dataset compared to random forests, linear regressions, and neural networks, which were all used by other contestants. In addition to desirable performance characteristics, GBRTs use different optimization functions depending on the problem, and can be tuned for both computational and accuracy constraints. Due to its decision tree roots, GBRT can also be used to extract information about its input variables through variable influence rankings and partial dependence plots. We hope that the results of this contest and the availability of GBRT in both Python and R open-source machine learning libraries encourage the atmospheric science community to apply the algorithm to their existing datasets.

In the spirit of open data and reproducibility, the contest website (www.kaggle.com/c/ams-2014-solar-energy-prediction-contest), data, and evaluation system will continue to be available to anyone wishing to compare their approaches against the contest winners. While new submissions will not appear on the leaderboard, people are still invited to compare their algorithm and discuss new findings on the contest forum.

ACKNOWLEDGMENTS. The contest was sponsored by the AMS Committees on Artificial Intelligence Applications to Environmental Science, Probability and Statistics, and Earth and Energy, and by EarthRisk Technologies. Will Cukierski from Kaggle helped set up the contest website and provided extensive technical support.

FOR FURTHER READING
The winning approach creatively combined the predictions from models that focused on different aspects of the input data as well as information about their spatial and temporal variability. At each Mesonet site, 13 GBRT models were trained. The first 11 models used input data from each GEFS ensemble member, and the other 2 used the medians and maximums of the GEFS variable values over all ensemble members. The models trained on each member incorporated data from the 4 GEFS grid points that surrounded each Mesonet site. The 5 intraday values for all 15 input weather variables were used from the 4 nearest grid points, resulting in 300 input values per day. Additional descriptive variables (latitude and longitude from the GEFS and Mesonet, the station ID, and the distances between the Mesonet site and GEFS points) were also included. The aggregated models were trained on either the median or the maximum value of the ensemble variables and on the sum of the intraday values. All of the models were trained and optimized with threefold continuous cross-validation over consecutive 4-year periods. The Python implementation of the GBRT was used.

Once the individual models had been trained, and once each produced solar energy predictions over the training time period, two optimized weighted ensembles were produced to create a consensus solar energy prediction for each site. The forecasts for each station were combined using the Nelder and Mead (1965) nonlinear optimization algorithm to minimize the MAE of the consensus prediction. A second optimized ensemble was created by optimally weighting the predictions at nearby Mesonet sites to match the predictions at a particular site. The two weighted ensemble predictions were then simply averaged and multiplied by 1.01 as a final bias correction. All of the models took 12 h to run and resulted in an error of 2.11 MJ m$^{-2}$. For comparison, the mean daily production of all Mesonet sites was 16.7 MJ m$^{-2}$, resulting in a mean global error of 13%. It should be noted that no manual feature engineering was performed; the GBRT and the optimization routines did all of the feature selection and distance weighting on their own.

Second place—Benjamin Lazorthes, Blia Solutions. As is often the case in predictive analytics, data preparation was the most important step in this project. Since the localization of the Mesonet stations did not coincide exactly with the position of the GEFS nodes (Fig. SBI),
some transformations were necessary in the training and testing datasets. For each of the 98 Mesonet stations, a linear interpolation of the four nearest GEFS points (weighted by distance) was carried out using the following formula:

\[
V_{\text{Mesonet}} = \frac{\sum_{i=1}^{4} w_i V_{\text{GEFS}}}{\sum_{i=1}^{4} w_i},
\]

in which \( w_i = \max(0, 1 - d) \) and \( d \) is the Euclidian distance from the Mesonet station to the nearest GEFS node (assuming that the smallest distance between 2 GEFS nodes is equal to 1).

Fifteen meteorological variables forecast each day at 0000 UTC for five different hours (at 1200, 1500, 1800, 2100, and 0000 UTC the following day) were provided. The 75 weather features were used without any prior selection. Additional features were created by spatially or temporally averaging the original 75 weather variables. The elevation, latitude, and longitude of the Mesonet stations, and the month of the observation, were also included. In total, 128 explanatory variables were defined.

All the data from the 98 Mesonet stations were gathered to obtain a single training set, a single testing set, and finally a single model for all stations. Some trials have been performed with separate datasets for each station, but they never gave more accurate predictions. Consequently, the training dataset had 501,074 rows and the testing dataset had 176,068 rows.

The best accuracy was achieved with GBRT, using the implementation directly available in R (gbm package) with the mean absolute error (MAE). Random Forests (Breiman 2001) were also evaluated, but were not retained because they were less accurate.

For each of the boosted trees, the following training settings were used: Mean Absolute Error (distribution = “laplace”), number of expansions between 2,000 and 3,000 (n.trees = 2,000 or 3,000), depth of the trees between 6 or 8 (interaction.depth = 6, 7 or 8), a learning rate of 0.05 (shrinkage = 0.05), an out of the bag proportion: 30% (bag.fraction = 0.7). An ensemble of 12 distinct gradient boosted regression tree models improved the accuracy by reducing the risks of overfitting.

The mean absolute error of the second-place model was 2,128,116 J m\(^{-2}\), as evaluated on the private test set. Knowing that the average daily incoming solar energy of the stations in the Mesonet is around 16,500,000 J m\(^{-2}\), it therefore corresponds to a mean absolute error of about 12.8%.

Some variables clearly appeared to be particularly important: the downward shortwave radiative flux average at the surface (dswrf) and the precipitable water over the entire depth of the atmosphere (pwat). Even if the other variables are less influential, they contribute to improve the global accuracy of the model. Table S1 gives the top 10 most important variables.

Figure SB2 is a 3D graphical representation of the model. The shape of the curve is typical of models obtained by combining several regression trees, and shows the dependence of the model on incoming solar radiation and precipitable water and how the two terms interact. As physically expected, increased precipitable water results in lower observed solar energy for a given amount of incoming solar radiation.
Third place—Owen Zhang, DataRobot. The third-place approach also used GBRTs, with the differences coming in the data preprocessing for training. Before training, the 11 forecast members were averaged to minimize the training data for efficiency purposes. Two GBRTs were trained, each on slightly different data. The first was trained on the data from the GEFS model point closest to the prediction point and the second was trained on a weighted average of the nearest 4 GEFS points. The data at each model point $p$ was distance-weighted by the longitude ($\phi$) and latitude ($\lambda$) distance to each Mesonet site ($s$) according to Eq. (SB2).

$$w_p = \frac{1}{(0.1 + \sqrt{(\phi - \phi_s)^2 + (\lambda - \lambda_s)^2})}.$$  \text{(SB2)}

Both models were trained on all 75 of the available features. Additional features included the day of the year, the longitude and latitude, and a derived feature called “daily differences in downward shortwave solar radiation ($\Delta S_d$).” This feature was defined in Eq. (SB3) as a weighted sum of the downward shortwave solar radiation for each available hour ($S_h$):

$$\Delta S_d = -0.5S_h(12) - 0.1S_h(15) + S_h(18) + S_h(21) + 0.8S_h(24).$$ \text{(SB3)}

The final prediction was a weighted vote of the two GBRTs. The weights were determined using cross-validation. Denoting the GBRT trained on the nearest data points as $GBRT_p$ and the one trained on the weighted average as $GBRT_w$, the final prediction for a Mesonet site $s$ was

$$\text{final}(p) = \frac{0.5 \times GBRT_p(s) + GBRT_w(s)}{1.5}. \text{ (SB4)}$$

Student Winner— Gilles Louppe, Department of EE and CS, University of Liege, and Peter Prettenhofer, DataRobot. This approach was similar in principle to the first-place winner (Eustaquio and Titericz) but made use of robust regression techniques to take uncertainty into account. It comprises two steps: First, a nonlinear interpolation technique, Gaussian Process regression (also known as kriging in geostatistics), is used to interpolate the coarse GEFS grid to the location of the solar energy production facilities. Second, GBRT is used to predict the daily solar energy output based on the interpolated model and additional spatiotemporal features.

Forecast variables measured at the GEFS locations are interpolated nonlinearly onto the Mesonet stations using Gaussian Processes (Rasmussen and Williams 2005). More specifically, for a given day and a given time period, a Gaussian Process models the value of a given forecast variable (e.g., temperature, humidity, etc.) with respect to the location of a station. Uncertainty in the forecast variables is taken into account by modeling the average value over the 11 members of the ensemble, where uncertainty in the ensemble measurements is specified as confidence intervals through the nugget parameter of the Gaussian Process. Using this technique, 75 forecast variables were interpolated per day in the dataset.

To enhance the final model, spatiotemporal variables were engineered and added to the 75 variables, including:

- Solar features (delta between sunrise and sunset)
- Temporal features (day of year, month of year)
- Spatial features (latitude, longitude, elevation)
- Nonlinear combinations of measurement estimates
- Daily mean estimates
- Variance of the measurement estimates, as produced by the Gaussian Processes

The best accuracy was achieved with GBRT. The least absolute deviation loss function was used for robustness, and all hyperparameters were optimized on an internal learning set. To further decrease variance of the model, several GBRT instances were built (using different random seeds) and their predictions averaged to form the final predictions. The ability of GBRT to handle outliers in the outputs by using robust loss functions is crucial in this context, due to the volatile nature of solar energy output. This pipeline was built on top of the Scikit-Learn machine learning library (Pedregosa et al. 2011), offering efficient implementations for both Gaussian Processes and GBRT.

The approach was evaluated on a dataset of daily solar energy measurements from 98 stations in Oklahoma. The results show a relative improvement of 17.17% and 46.19% over the baselines, Spline Interpolation, and Gaussian Mixture Models, respectively.

### Table S1. Variable influence rankings for the second-place gradient boosting algorithm.

<table>
<thead>
<tr>
<th>Name</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>dswrf (2100 UTC)</td>
<td>20.9%</td>
</tr>
<tr>
<td>dswrf (1800 UTC)</td>
<td>13.1%</td>
</tr>
<tr>
<td>dswrf (0000 UTC)</td>
<td>11.5%</td>
</tr>
<tr>
<td>dswrf (1500 UTC)</td>
<td>4.2%</td>
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<tr>
<td>pwat (2100 UTC)</td>
<td>3.8%</td>
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<td>pwat (1500 UTC)</td>
<td>3.7%</td>
</tr>
<tr>
<td>pwat (1800 UTC)</td>
<td>3.6%</td>
</tr>
<tr>
<td>Month</td>
<td>3.5%</td>
</tr>
<tr>
<td>pwat (0000 UTC)</td>
<td>3%</td>
</tr>
<tr>
<td>pwat (1200 UTC)</td>
<td>2%</td>
</tr>
</tbody>
</table>
It's election season at AMS. The 2015 candidates for AMS president-elect are Matthew Parker, CCM, and John Toohey-Morales, CCM/CBM. This year’s candidates for AMS councilor are: Private sector—Phil Ardanuy, Ron Birk, Jim Black, CCM; Government—Andrea Bleistein, Melinda Marquis, Adm. Jonathan White; Academic—Ankur Desai, Sue Ellen Haupt, James Kinter.

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

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

AMS PRESIDENTIAL CANDIDATES

MATTHEW J. PARKER

Demand for services in the weather, water and climate enterprise is ever increasing. Pressures faced on budgets, scientific progress, and mankind’s ongoing challenges with infrastructure, human health, safety, and the environment are amplifying. Further, we are necessarily stretching our minds to keep up with an observed, modeled, and social data avalanche that threatens to exceed our ability to apply these burgeoning resources. Our working model for enterprise interactions amongst the government, academic, and commercial sectors has been effective, but that effort requires critical, ongoing attention. We need to be highly responsive to today’s world of fast moving information with the best answer possible, but we are spread very thin. That’s precisely where the AMS comes into play.

The Society’s strength is our diversity in backgrounds, expertise, and viewpoints. Smartly, we focus our attention inward and outward through an incredible set of technical meetings, information exchange with policymakers, and journals that lead our profession. The Society is engaging the meteorological societies of other countries, and members strive to attain certifications in broadcasting (CBMs) and consulting (CCMs).

As President, I will represent our Society domestically and abroad. I will encourage productive and unifying discourse amongst the government, academic, and commercial sectors. I will encourage young colleagues to take on roles of increasing responsibility and encourage our senior professionals to continue their critical efforts supporting the foundation of our science. And I will be attentive to your concerns as the Society evolves. We have a proud history in the AMS, and what we say and do matters greatly.

MATTHEW J. PARKER

MATTHEW J. PARKER is a senior fellow meteorologist within the Atmospheric Technologies Group of DOE’s Savannah River National Laboratory (SRNL). Matt joined SRNL in 1989 after receiving a bachelor (1986) and master (1989) of science in meteorology from North Carolina State, and is responsible for oversight of SRNL’s 12-tower mesonet, including an instrumented television transmission tower, and a ceilometer. Matt led the establishment of “Aiken Site” AmeriFlux Tower with the University of Georgia and the “South Carolina Tower” trace gas monitoring station of NOAA (GMD). Presently, Matt is leading a solar energy initiative with major utilities to study the meteorological aspects of clouds in the southeastern United States.

Matt is a CCM (#570), an AMS Fellow (2006), and is past-commissioner (incoming and commissioner, 2010–16) of the Commission on the Weather, Water and Climate Enterprise (CWWCE). Matt was a member of the committee that established the CWWCE and became the inaugural chair of the Board on Enterprise Communication (2005–09). Matt cochaired the Policy Statement on National Weather and Climate Priorities writing team (2008–09) and organized three short courses on weather entrepreneurship. Other service includes tenures on the Board of Private Sector Meteorologists, the Committee on Measurements, and the Ad Hoc Committee on the Continuing Professional Development of CCMs. Matt has served as an anonymous reviewer for BAMS, the Journal of Technology, and other journals.

Matt is a Past-President of the National Council of Industrial Meteorologists (2004), a charter member (1991) of the Nuclear Utility Meteorological Data Users Group, and a past-chair of the ANSI/ANS 3.11 standard for “Determining Meteorological Information at Nuclear Facilities.” Matt has served as an SME for the DOE Meteorological Coordinating Council’s “Assist Visit” program and is co-inventor of “Nondestructive Test Method for Assessment of Subterranean Tower Anchor Rods” (6,311,565), which has been licensed to the cellular industry.
The AMS has been the cornerstone of my professional career development. My experiences working with the Society have been invaluable and have led to opportunities that I would not have realized otherwise. As a past-commissioner, I understand and appreciate how to work with the Council, commissions, and members. Leading the AMS as President would be an incredible honor and challenge, and I am enthusiastically willing to serve in this highly distinguished position.

JOHN TOOHEY-MORALES

Are atmospheric and related oceanic and hydrologic sciences more paramount to society than ever? I would argue that they are. More people are living in harm’s way, and our growing and aging infrastructure is exposed to disruptive or damaging events that unfold at the widest of time scales—from short-fused severe weather to long-term changes in climate. The value of accurate, timely, detailed, understandable, and customized information—that only we can provide—is rapidly increasing. And the way we provide it is rapidly changing.

As we approach our 100th birthday, the AMS has never been more relevant. The implementation of Weather Ready Nation has energized our public servants as they help protect increasingly vulnerable communities. The academic sector has never been more essential, as research and an efficient research-to-operations pipeline becomes indispensable. And our country’s commercial weather and climate industry has become the fastest-growing segment of the enterprise. Our broadcast meteorologists are the daily face of science for millions, while our Society’s young professionals are spearheading novel ways to be great science communicators in an era when it’s sorely needed.

In the midst of this changing landscape, the AMS President-elect—supported by 14,000 members and 100 boards and committees—can lead the way in identifying and fostering best practices. Because my career has spanned the private, public, and academic sectors of our profession, I can appreciate all angles. Your perspectives are important, whether you’re a researcher and professor, a NOAA forecaster, a broadcast meteorologist, an oceanographer, or a climate scientist. Your ideas have value, whether you’re young or “more seasoned.” I want a Society that’s inclusive and diverse, where friendship and collaboration flourish in an environment where all disciplines and points of view are respected. While valuing all viewpoints, new ideas can and should be incorporated into the Society. I am grateful for the opportunity to serve you.

JOHN TOOHEY-MORALES

John Toohey-Morales is chief meteorologist at WTVJ NBC-6 in Miami, FL, and the founder of ClimaData, a small commercial weather firm. During his 31-year operational meteorology career, Morales has worked in the public sector (as a lead forecaster for the NWS) and in the private sector (as a Certified Broadcast Meteorologist and Certified Consulting Meteorologist). He’s also been an adjunct professor of meteorology at St. Thomas University in Miami. John attained his CCM (#589) designation in 1997, and is one of only a handful of AMS members with both the CCM and CBM (#5) accreditations.

Morales—an AMS Fellow—served for six years as the Society’s Commissioner on Professional Affairs, and as such was an ex-officio member of the AMS Council. He has chaired or participated in another half-dozen AMS committees and boards. Morales was honored with the AMS Award for Outstanding Contribution to Applied Meteorology in 2007, the AMS Award for Broadcast Meteorology in 2004, and the NWA Broadcaster of the Year Award in 2003. Morales is also Past-President of the National Council of Industrial Meteorologists (NCIM), as well as a member of the National Weather Association (NWA).

Back in his NOAA days, Morales was part of the Department of Commerce Silver Medal-winning NWS San Juan team for “distinguished, and at time heroic, service during . . . Hurricane Hugo.” As a broadcast meteorologist, he’s won three regional Emmy awards. His experience in all sectors of the weather enterprise led to his selection as one of the original members (still serving) on the Environmental Information Services Working Group of NOAA’s Science Advisory Board. Previously, John served on the National Academies NRC Committee studying the modernization of the NWS, and coauthored the report “Weather Services for the Nation: Becoming Second to None.”

John attained his degree in atmospheric sciences from Cornell University in 1984. Masters-level coursework in remote sensing and tropical meteorology was completed during WMO-sponsored training at the National Hurricane Center and the University of Miami in 1988.
Our upcoming centenary provides a meaningful opportunity for us to renew and transform our vision—to be as relevant 20 years from now as we are today.

The three-component nature of our Society, and its inherent diversity, are solid foundations for building and sustaining membership across the spectrum of Earth system sciences. As your Council member, I will focus on ensuring that the academic, operational, and private-sector components of our Society each remain vibrant, while collaborating more fully to produce synergies far outweighing the sum of our parts.

Together, we face three challenges:

- Creating a shared vision that encourages the next generation across each of three components to join and actively participate as we build a weather-, water-, and climate-ready nation. We do well as a scientific organization and with students, but must do more on the professional side to attract and retain young members by reminding them of the benefits their professional society provides them.

- Embracing a dynamic and ever-changing information technology revolution within observation systems, modeling and data assimilation systems, forecast systems, information management and dissemination systems, analytics, applications, and social media.

- The world demand for environmental intelligence in all its forms will only grow. In a world where information access is broad and instantaneous, and information interpretation abundant, AMS must not only serve as a voice of reason, but must also raise its voice of reason above the noise.

  The Society has done this effectively within our community. Now, we must position the Society to serve much broader audiences.

My 30+ years’ experience as both an academic scientist and private sector engineer working on state-of-the-art observing and decision support systems has given me the insight to help address these challenges smartly. I pledge to remain steadfast in my support for achieving this vision, and ask for your support.
RON BIRK (PRIVATE SECTOR)

The AMS enterprise spans the value chain from observations to models to decision support in our mission to promote communications and education in weather, water, and climate. There are inherent challenges in maintaining a balance across the value chain as science and technologies evolve. A key approach to overcoming these challenges is to strengthen the network of relationships between academia, government, and private-sector professionals working in observations, models, and decision support. The Weather Ready Nation Roadmap 2.0, Fair Weather, and Second to None reports call out benefits of building effective collaboration and communications throughout the diverse enterprise to deliver high-caliber information for impact-based decision support.

Coupling collaboration and communications builds confidence in environmental products and policies to guide decisions, especially decisions affecting long-term sustainment of water and other natural resources. I see opportunities to bring together professionals from diverse sectors spanning the value chain within AMS through innovative venues to share information and build confidence on key topics germane to protecting life and property.

For decades, we have seen the value of AMS members coming together to address and overcome challenges with effective applications of atmospheric, oceanic, and hydrologic sciences. I have seen impressive benefits result from bringing people together from multiple agencies in my role as cochair of the U.S. Group on Earth Observations (USGEO) and working groups in the U.S. Climate Change Science and Technology Programs. And recently, we have seen results in extending the reach of AMS to a broader audience by coordinating panels of professionals on social media Hangouts dedicated to key topics including “Overcoming Extreme Weather,” “Extreme Precipitation,” and “Women in Weather.”

I welcome serving on the Council and furthering collaboration and communications using innovative tools and technologies to enable AMS professionals to expand their reach across the country and around the world.

RON BIRK

Ron Birk is program manager for weather and science solutions for Northrop Grumman Information Systems in McLean, Virginia. He engages with the weather enterprise to advance value-add decision support leveraging advancements in science and technology through next-generation observing systems and models. He is responsible for developing and implementing strategy and solutions to extend benefits of science-based information systems to serve demanding societal needs for environmental systems and services. Ron is a member of the Environmental Information Services Working Group of the NOAA Science Advisory Board, and serves as chair of the Special Events Working Group for the American Astronautical Society (AAS).

Birk earned his B.S. in physics from the University of Notre Dame in 1982. He has over 30 years of experience in the development and management of remote sensing and information system solutions for environmental decision support integrating related Earth science and technologies for practical applications to benefit society.

In a previous role with Northrop Grumman, Birk served as director, business development for civil & military aerospace systems. Prior to joining Northrop Grumman, he worked for NASA as the director of the applied sciences program in the Science Mission Directorate, where he cochaired the U.S. Group on Earth Observations and chaired the Measurement and Monitoring Systems Working Group in the U.S. Climate Change Technology Program. His career spans the value chain, from developing remote sensing instruments—including the Airborne Terrestrial Applications Sensor (ATLAS)—to managing an Airborne Instrument Test System (AITS), Commercial Remote Sensing Program, initiating business for EarthWatch Inc. and Intermap Technologies for their high-resolution imagery and digital elevation model (DEM) products, to the NASA Applied Sciences program collaborating with 12 federal agencies, to leading a Global Change Monitoring Campaign for Northrop Grumman.

Along with his membership in AMS, Birk is a member of the AAS and the Project Management Institute.
The AMS has been an integral part of me from the start of my career. I began as a student member, and first volunteered to be cochair of the 4th annual Student Conference as a way to hone my networking skills and learn about the weather, water, and climate enterprise. As I’ve taken on new and exciting professional opportunities, my volunteer involvement with many AMS boards and committees has grown. Being involved with AMS has allowed me to expand my own professional knowledge and connections as well as be a better steward for NOAA. My commitment to AMS as a member and volunteer has always been an important part of my professional journey. It would be an honor to serve as Councilor for AMS and work together to meet the many challenges we face as a Society. Some specific challenges I see facing AMS that would have my attention and focus include:

- Maintaining and increasing the relevancy of the Society for itself and for its entire membership. AMS membership has broadened over time and has a multitude of expertise, which should be leveraged to ensure AMS continues to promote the development and dissemination of information and education on the atmospheric and related oceanic and hydrologic sciences.
- Continuing to attract early- and middle-career professionals as well as an overall diverse membership. AMS needs to ensure it has its pulse on our ever-evolving enterprise, and by attracting a diverse set of early- and middle-career professionals it can identify those opportunities and challenges for the Society to remain relevant.
- Striving for transparent communication, discussion, and partnerships on topics relevant to our enterprise among members as well as with AMS affiliations and nontraditional groups. AMS is well established with the help of its journals and conferences acting as mechanisms of communicating to its members and beyond. Greater attention to all aspects of communication both internal and external to AMS should continue to be a priority.
- Establishing the Society’s role in helping to build a Weather-Ready Nation. After having spent my career in NOAA on a broad range of missions, including operations, science and technology, external affairs, policy, and organizational change, I continue to support the agency and the nation in this grand challenge to become more responsive and resilient to weather. NOAA cannot build a Weather-Ready Nation on its own, and this is where a professional organization like the AMS must play a key role.

There are many challenges and opportunities which the AMS faces, and you have my commitment and enthusiasm for our Society and to our science to continue to make AMS a valued and trusted professional society.
Our Society faces several challenges as we move toward our second century, chief among them meeting the needs of our membership and remaining relevant as the weather enterprise evolves ever more rapidly. In order to meet current members’ needs, and to be able to attract new members, the AMS must demonstrate flexibility in order to be seen as relevant to the next generation of meteorologists that is now entering its ranks.

Nowhere is the pace of change more evident than in the private sector, which is now the largest and fastest-growing sector in the weather enterprise, although change is happening across all sectors. In the rapidly changing world of the Internet, social media, ever-faster communications, and fewer and fewer restrictions on computing and data, professionals in all sectors are now reaching more and more people with products that help them understand and cope with weather and climate. It is these new professionals who must become part of the fabric of the AMS in the twenty-first century.

The AMS has a proud legacy of scientific leadership and professional conduct that remains its chief asset in today’s world. Because of its strong and diverse membership, the AMS can provide the collective support and insight of a broad variety of scientists, engineers, and educators who together have the capacity to meet the current challenges and environmental risks we face today.

I am proud to be a member of the AMS, and I will strive to balance the needs of members with the practical aspects of running an organization. It is my belief that if the AMS can serve its members well, it will serve society well for another century.

JAMES H. BLOCK, CCM

James H. Block, CCM, is the director of weather content at Schneider Electric Weather. He has provided weather forecasts, software development, and meteorological consulting to clients in aviation, energy, transportation, and weather systems for 35 years. Schneider Electric is a company that delivers weather solutions to commercial businesses around the world, including electric and gas utilities, energy and commodity trading companies, agricultural operations, surface transportation, aviation, and even weather systems at airports around the world.

At Schneider Electric, his mission is to establish world-class excellence in the breadth, integrity, and quality of the global weather information, forecasting, and consulting services that support the growth of Schneider Electric’s Cloud Services and Global Solutions divisions. This includes all of the weather content used in the weather products and services provided by Schneider Electric, including weather forecasts and products used every day by over 100,000 global businesses to make critical decisions.

Block earned his M.S. (1979) and B.S. (1977) degrees from the University of Wisconsin—Madison. He worked in a variety of forecasting roles, including as an aviation forecaster at Republic Airlines, before joining the Kavouras Corporation. At Kavouras, Block launched the weather forecast department that today is known as MetOps. At the same time, he became increasingly involved in the development of digital weather information services, including radar, satellite, and other types of weather information that became the foundation of a high-bandwidth weather distribution system that preceded the Internet. In 1989, Block became a CCM, shortly after becoming the vice president of systems development, overseeing the development of several patented programs, including the first ground-corrected satellite images, and the first three-dimensional satellite images. When Kavouras became Meteorlogix after the first of several corporate acquisitions, he became the chief meteorologist, which included responsibility for all aviation and agricultural weather products, and in 2012, Block helped to develop a new, patented turbulence forecast system. With the corporate change to Schneider Electric, Block moved to the Netherlands for two years and served as the managing director of the Weather Systems division, and began his current responsibilities upon his return earlier this year.

Block has served the weather enterprise in many capacities over his career, including on AMS committees such as the Intelligent Transportation Committee and the Board for Private Sector Meteorologists (which he chaired for two years), and several ad-hoc committees. Block has also been a member of the National Council of Industrial Meteorologists since 1993, and served as its President in 2002. In 2010, Block was elected as a Fellow of the AMS.
AMS is the place for scholarly communication, professional activities, and outreach in meteorology. There was no question about joining 13 years ago as a Ph.D. student preparing my first abstract, and it is my goal that we continue to serve as home for all meteorologists from student to professional. However, maintaining our services requires a solid funding model and active member engagement. I would be honored to serve as a forceful advocate for early-career professionals, interdisciplinary scholars, a diverse membership, affordable open-access publishing, and higher education.

I may not be as accomplished as other candidates. I am more mid-career. I am a meteorologist, but my research spans into ecology. I am active in AMS, but share my disciplinary home with the American Geophysical Union. My scholarly community attends AMS specialty meetings, not the Annual Meeting.

So, why me? I suppose my limitations could actually be viewed as strengths. I have my ear to the ground to anxieties of young scientists regarding the tight academic labor market. As graduate chair, I am concerned with leaky pipelines, as fractions of female and minority scholars decline with each career stage. As a tenured faculty member, I worry about modernizing our curriculum and erosion of faculty governance. Straddling societies, I have shepherded meeting, publication, and outreach innovations across multiple organizations, understanding bottlenecks to action.

We face a major challenge in erosion of public trust and funding in our field, even with increasing demand for our degree, broadening of private-sector opportunities, and pressing policy needs. Lack of investment is putting the weather–climate enterprise in America behind Europe and Asia. Meanwhile, a drop in federal research support threatens fundamental advances made by AMS members, especially junior faculty.

AMS could be a catalyst on re-envisioning education and training of future meteorology professionals. It is time to revisit guidance on career pathways and statements on sustainable funding and publication models. I would be privileged to help lead this conversation.

ANKUR R. DESAI is associate professor and graduate program chair in atmospheric and oceanic sciences at the University of Wisconsin—Madison, where he is also faculty affiliate in the Nelson Institute For Environmental Studies Center for Climatic Research and the College of Engineering Program in Freshwater and Marine Science. Desai received his Ph.D. in meteorology from Pennsylvania State University, M.A. in geography from the University of Minnesota, and B.A. in environmental studies and computer science from Oberlin College. He has also held positions as a post-bachelor’s intern with the U.S. EPA, a post-master’s research fellow in forest resources at U. Minnesota, and an NCAR Advanced Study Program postdoctoral fellow.

As a micrometeorologist, Desai’s research focuses on the role of temporal and spatial scales in biologically mediated surface–atmosphere exchanges of trace gases, energy, and momentum. Ankur is closely involved with the DOE Ameriflux Project, as a core-site principal investigator of four eddy covariance flux tower facilities. He makes, synthesizes, and assimilates in situ ecological, and airborne, tower, and satellite-based atmospheric boundary layer observations to test scale hypotheses in land surface and climate models.

His research has been supported by more than $10 million of research funding from federal and nonprofit agencies in the past decade, including NSF, NASA, NOAA, DOE, and USDA, which has led to nearly 80 peer-reviewed publications, including in several AMS journals, and generation of eight graduate or undergraduate theses, with another five in progress. Desai teaches courses and runs summer schools in climate processes, ecosystem ecology, and boundary layer meteorology. Last year, he was appointed MICMoR Visiting Scientist at the Karlsruhe Institute of Technology Campus Alpin in Garmisch-Partenkirchen, Germany.

Desai served as an early member of the recently formed AMS Board on Atmospheric Biogeosciences, as chair of the AMS Committee on Agricultural and Forest Meteorology for the past six years, and cochair of the first joint meeting between the two groups. He is also an editor for Journal of Geophysical Research, panelist for NSF/NCAR Observing Facilities Assessment Panel, member of the USGCRP North American Carbon Program science steering group, and chair of two working groups for the National Ecological Observatory Network, Inc.
Whenever I attend an AMS event, I’m always delighted by the positive energy and engagement. We have a great community of professionals and students engaged in all aspects of the weather, climate, and water enterprise. Whether from academia, government, or industry, we are working together to advance knowledge and to apply it to critical issues. The important challenge to AMS is to harness this knowledge and energy in the most effective way to work together with our diverse skills and abilities to address human and environmental needs. AMS becomes the focal point for addressing issues and answering questions that arise. In our evolving environment, how do we collaborate to provide the information and support to the populace on our ever-changing weather and climate? How do we leverage the expertise of our members and diversity of thought to engage in multidisciplinary conversations and efforts to support society’s needs? How can we better organize and act to address the challenges of the future? AMS has been a leader in bringing the sectors together; but since the world is not static, we must be willing to evolve to meet emerging needs.

As an AMS councilor, I would work with colleagues within the framework of the commissions, boards, and committees to foster yet deeper collaborations and seek to engage the capabilities of the individual members as well as the various sectors to develop the synergy of this great Society in order to accomplish things not possible alone, thus engaging our weather, climate, and water expertise to make the world a better place.
It is a great honor to be nominated for AMS Councilor. The AMS is both strong, with a long tradition of scientific rigor and intellectual members of high personal integrity, and unique, bridging the three sectors of academia, government, and business. Nevertheless, serious challenges face the AMS that demand visionary leadership. First, there are fundamental research challenges, because the atmosphere cannot be studied in isolation from the rest of the Earth system and human society. There are gaps in our understanding of fundamental aspects of weather and climate, spanning an enormous range of spatial and temporal scales, from individual clouds to the response of the Earth system to unprecedented forcing by human activities. The research challenges extend beyond meteorology, not only to the physical and biological sciences, but also to studies of human behavior. The AMS is central to addressing these research problems, because it is the only society that is both academic and professional and covers the full range of these issues. Second, there are institutional challenges that represent a serious, if not existential, threat to our enterprise. For example, while there is keen interest in more effectively translating research results into operations and applying those results for societal benefit, our institutional alignments do not promote these types of transitions. More creative and nimble institutional arrangements are needed. Perhaps more serious, there is a long-term trend of marginalization of our science that has led to sharply diminished budgets just when critical research and societal issues require large infusions of resources. Again, the AMS can act to slow or reverse these trends through its influence on decision makers. Third, the rapid evolution of our science—through the deployment of advanced observing systems and the employment of enormous computing and data storage capabilities—presents a challenge to all three sectors, not only to stay technologically current and relevant but also to stay connected. It falls on the AMS to provide the necessary leadership to help academia, government, and the private sector take best advantage of the accelerating changes in our field.

James L. Kinter is professor of climate dynamics in the Atmospheric, Oceanic and Earth Sciences Department at George Mason University and director of the Center for Ocean–Land–Atmosphere Studies (COLA), a research center that he helped establish, with over 25 research scientists and affiliated faculty. He received an A.B. in mathematics and M.S. and Ph.D. degrees in geophysical fluid dynamics, all from Princeton University. He was previously a National Research Council research associate at the NASA Goddard Space Flight Center and a faculty member at the University of Maryland.

Kinter has conducted research in climate variability, predictability, and prediction, using global reanalysis datasets and models of the coupled climate system. He has made contributions to the predictability and prediction of El Niño and the Southern Oscillation, the Asian monsoon, and North American drought and floods. He has studied secular shifts and decadal trends in climate and the impact of spatial resolution on model fidelity. Kinter has also been instrumental in the development and support of the widely-used Grid Analysis and Display System (GrADS). He has led several highly productive international research collaborations, including the International CLIVAR Climate of the 20th Century project, and Projects Athena and Minerva.

Kinter is a member (since 1983) and Fellow of the AMS and has served as a reviewer for several AMS journals. He has served on many advisory and review panels in the atmospheric and computational sciences, notably as the first chair of the TeraGrid Scientific Advisory Board and with long service on the NCAR CISL High-Performance Computing Advisory Panel and the Climate Simulation Laboratory Advisory Panel. He served on the NSF committees on Cyberinfrastructure for Research and Development in Atmospheric Sciences (cochair), Petascale Computational Facilities for Geosciences, Advisory Committee for Geosciences, and Advisory Committee for Cyberinfrastructure. He is currently a member of the CESM Advisory Board. Kinter has served on the NOAA Climate Test Bed Advisory Board, the UCAR Community Advisory Committee for NCEP (cochair), and the NOAA MAPP program task forces on CMIP5 (chair), Climate Model Development (cochair), and Climate Prediction. He has served on National Academy of Sciences panels on climate modeling strategy and the NSF AGS division. He helped establish the Journal of Advances in Modeling of Earth Systems and organized several critical international workshops, most recently the Symposium on Predictability in the Midst of Chaos.
The key challenges facing the AMS are the key challenges facing the global society. However, the AMS is particularly well-qualified to address these challenges and help the global society realize a brighter future. The Society is well-poised to lead in three realms: First, understanding natural variability and anthropogenic climate change, as well as providing the required information to support adaptation and mitigation, requires cross-disciplinary work. For instance, those working to reduce greenhouse gas emissions via renewable energy can be most effective if their expertise spans many areas of atmospheric science, engineering, finance, and social sciences. Experts who step outside their comfort zones and learn the language, priorities, and methods of other disciplines make an investment that yields a great return. The AMS provides ample opportunities for incubating cross-disciplinary work: inviting experts from other disciplines to attend and actively engage in AMS meetings, participating in meetings of other disciplines’ professional societies, and collaborating via AMS committees with professional societies in other fields.

Second, the exponential growth of computing speed, nanotechnology, robotics, and artificial intelligence necessitates greater attention to and deliberation about society’s adoption of technology. The evolution of technology affects the AMS and global society in ways we do not yet fully understand. One example is the displacement of workers by new technology. The challenge is to maximize the benefits and minimize the harm of the accelerating rate of technological change.

Third, a widespread antiscience sentiment in the United States, along with the degradation of well-reasoned civic discourse, is a risk to the AMS and society in general. The AMS can address this troubling trend in multiple ways. The AMS Council is responsible for issuing statements on behalf of the Society. Of the statements it issues, the information and policy statements are most useful in countering the antiscience movement. Additionally, the AMS educates members of the public, private, and academic sectors in other ways, both formal and informal, on topics on atmospheric, oceanic, and hydrologic science. In doing so, the AMS helps protect and improve the quality of educational curricula and scientific information available to the public. While providing reliable information is critically important, the Society should bear in mind that simply being a source of good information has been shown to be an ineffective means of persuading those whose views do not shift when faced with a preponderance of countervailing data. While disseminating the best information available, the Society also must consider methods of finding common ground with those who question well-established science, with the aim of building more productive and reasonable civic discourse.

As an AMS Councilor, I would encourage multidisciplinary work, focused attention on the potential consequences of extremely rapid technological advances, and careful promulgation of arguments and decisions based on science and reason.

MELINDA MARQUIS (GOVERNMENT SECTOR)

Melinda Marquis is the renewable energy program manager at the NOAA Earth System Research Laboratory (ESRL), where she leads efforts to improve observations, foundational weather forecast skill, and climate information for wind and solar power applications. She represents NOAA’s Oceanic and Atmospheric Research (OAR) line office on the NOAA Energy Team. She joined NOAA ESRL in 2007, after serving as deputy director for the Intergovernmental Panel on Climate Change (IPCC) Working Group I. Dr. Marquis is chair of the AMS Board on Global Strategies. She earned her Ph.D. in organic chemistry from the University of Colorado in 1995.
Our society faces daunting challenges as we look for ways to address the recognized, but not well-understood, changes that are occurring with our atmosphere, ocean, cryosphere, and overarching climate. While scientific evidence and popular acceptance of the physical changes mounts, our nation and our global society are lethargic in the willingness to make necessary decisions and invest appropriately in efforts to (1) adapt and respond to the changes we recognize, (2) better understand and communicate the complex cause-and-effect dynamics of these changes, and (3) alter or mitigate the detrimental physical effects our growing population and activity are having on our planet and society.

In 2004, Admiral James Watkins and the Ocean Commission stated that “The nation lacks effective mechanisms for incorporating scientific information into decision-making processes in a timely manner.” This remains largely true today. Our physical scientific community must redouble efforts and develop new strategies and approaches, not to just better inform perceived decision-makers, but to effectively lead our nation and international community in requisite decision-making.

If elected to the AMS council, I will actively embrace the opportunities presented by this position to lead progress along these lines. This will involve establishment of concrete goals and objectives for the scientific community, and related goals and objectives for national leadership at the federal, state, and local levels—all oriented toward improved decision-making through improved understanding and prediction of change at all geographic and temporal scales. I believe we are at a perfect juncture for AMS to effect real, positive decision-making change by leading the coherence of research, operational analysis/prediction, and governing organizations. I am excited about having an opportunity to take this on as a member of the AMS council.

REAR ADM. JONATHAN W. WHITE

REAR ADMIRAL JON WHITE was born in Panama City, Florida. His father was a World War II Army Air Corps veteran and Purple Heart recipient; his mother supported the war through her work in Oak Ridge, TN. His passion for the Navy and oceanography began at age seven, thanks to the influence of a Navy diver who lived next door.

White earned a Bachelor of Science degree in oceanographic technology from the Florida Institute of Technology in 1981 and holds a master’s degree in meteorology and oceanography from the U.S. Naval Postgraduate School, where he graduated with distinction in 1991.

After working at sea as a civilian oceanographer, White was commissioned through Navy Officer Candidate School in 1983. Since then, he has had numerous operational assignments that have involved using meteorological and oceanographic knowledge to advance safety and success in military operations at sea and ashore around the globe.

As a Commander (O-5), White commanded the Naval Training Meteorology and Oceanography Facility in Pensacola, Florida, which provided operational forecasting for all naval stations in the south-central United States. As a Captain (O-6), White was the 50th Superintendent of the U.S. Naval Observatory, responsible for providing precise time and astrometric services to the DoD and critical national infrastructure.

White was selected as a flag officer and honorary Chief Petty Officer in 2009 and served as Commander, Naval Meteorology and Oceanography Command, responsible for a mixed military and civilian workforce of over 3,000 people, at sea and ashore, performing meteorology and oceanography operations around the globe. During this tour, White dramatically improved and restructured the Navy’s operational maritime weather forecasting operations, leading to the establishment of the two Fleet Weather Centers, in Norfolk, Virginia, and San Diego, California.

White was promoted to the rank of Rear Admiral (upper half) in August 2012 as he assumed his current duties as Oceanographer and Navigator of the Navy, which include director, Task Force Climate Change, and Navy Deputy to NOAA. In this position, White leads the Navy’s efforts associated with climate change, including the Arctic, sea level rise, and associated atmospheric/oceanographic/climate-prediction capabilities.
**NEW MEMBERS**

The Council has approved the election of the following candidates to the grade of **Full Member**:

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<tr>
<th>Toru Adachi</th>
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<td>Matthew Andrews</td>
<td>Nicole Gallicchio</td>
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<td>Lori Armstrong</td>
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<td>Tyler A. Southard</td>
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<td>Samuel LeBlanc</td>
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The Executive Committee has approved the election of the following candidate to the grade of **Affiliate Member**:

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

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

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The Call for Papers and Calendar sections list conferences, symposia, and workshops that are of potential interest to AMS members. Complete information about events listed in the calendar can be found on the meetings page of the AMS website, www.ametsoc.org. New additions to the calendar are highlighted.

To list an event in the calendar, please submit the event name, dates, location, and deadlines for abstracts, manuscripts, and preregistration to amsmtgs@ametsoc.org. For a submission to appear in a given issue, it must be submitted at least eight weeks prior to the month of publication (that is, to appear in the March Bulletin, the submission must be received by 1 January).

**AMS MEETINGS**

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**2015**

**AUGUST**

16th Conference on Mesoscale Processes, 3–6 August, Boston, Massachusetts
Abstract deadline: 6 April 2015
Preregistration deadline: 22 June 2015
Manuscript deadline: 4 September 2015
Initial announcement published: Sept. 2014

2015 AMS Summer Community Meeting, 4–6 August, Raleigh, North Carolina

**SEPTEMBER**

AMS Short Course on Dual-Polarized Phased Array Antennas for Weather Radars, 12 September, Norman, Oklahoma

AMS Short Course on Open Source Radar Software, 13 September, Norman, Oklahoma

AMS Short Course on Radar Aerocology, 13 September, Norman, Oklahoma

AMS Short Course on CM- and MM-Wavelength Radar Applications, 13 September, Norman, Oklahoma

AMS Short Course on Basic Principles of Weather Radar Polarimetry and its Operational Applications, 13 September, Norman, Oklahoma

37th Conference on Radar Meteorology, 14–18 September, Norman, Oklahoma
Abstract deadline: 1 May 2015
Preregistration deadline: 5 August 2015
Manuscript deadline: 18 October 2015
Initial announcement published: Dec. 2014

**OCTOBER**

11th International Conference on Southern Hemisphere Meteorology and Oceanography, 5–9 October, Santiago, Chile

**JANUARY**

15th Annual AMS Student Conference, 9–10 January, New Orleans, Louisiana
Abstract deadline: 1 October 2015
Preregistration deadline: 15 December 2015
Initial announcement published: Feb. 2015

Fourth Annual AMS Conference for Early Career Professionals, 10 January, New Orleans, Louisiana
Preregistration deadline: 15 December 2015
Initial announcement published: May 2015

Preregistration deadline: 1 December 2015
Initial announcement published: TBD

*Marvin Geller Symposium: A Celebration of His Diverse Contributions to the Atmospheric Sciences, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: April 2015

*Peter Lamb Symposium, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

*Mario Molina Symposium, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

*32nd Conference on Environmental Information Processing Technologies, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*30th Conference on Hydrology, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

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*An exhibit program will be held at this meeting.
Initial announcement published: April 2015
Manuscript deadline: 12 February 2016
Preregistration deadline: 1 December 2015
Abstract deadline: 3 August 2015

*28th Conference on Climate Variability and Change, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: April 2015

*22nd Conference on Applied Climatology, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration Deadline: 1 December 2015
Manuscript Deadline: 12 February 2016
Initial announcement published: March 2015

*25th Symposium on Education, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

23rd Conference Probability and Statistics in the Atmospheric Sciences, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: April 2015

Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

19th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: April 2015

*18th Conference on Conference on Atmospheric Chemistry, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

*18th Symposium on Meteorological Observations and Instrumentation, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

* An exhibit program will be held at this meeting.

NEW! PRINT & CD FORMATS

“Professor Lackmann has prepared an excellent synthesis of quintessential modern midlatitude synoptic-dynamic meteorology.”

—LANCE BOSART, Distinguished Professor, Department of Atmospheric and Environmental Sciences, The University of Albany, State University of New York

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GARY LACKMANN

The past decade has been characterized by remarkable advances in meteorological observation, computing techniques, and data-visualization technology. Midlatitude Synoptic Meteorology links theoretical concepts to modern technology and facilitates the meaningful application of concepts, theories, and techniques using real data. As such, it both serves those planning careers in meteorological research and weather prediction and provides a template for the application of modern technology in the classroom.

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AMERICAN METEOROLOGICAL SOCIETY  AUGUST 2015  1411
*14th Conference on Artificial and Computational Intelligence and its Applications to the Environmental Sciences, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*11th Symposium on Societal Applications: Policy, Research and Practice, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*10th Annual CCM Forum, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: April 2015

*Fourth Symposium on the Weather, Water, and Climate Enterprise, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*Fifth Aviation, Range and Aerospace Meteorology Special Symposium, 13 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*14th History Symposium, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: April 2015

Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: TBD

*Special Symposium on Hurricane Katrina: Progress in Leveraging Science, Enhancing Response and Improving Resilience, 12 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

*14th Symposium on the Coastal Environment, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*13th Conference on Space Weather, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*Sixth Symposium on Advances in Modeling and Analysis Using Python, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*Eleventh Symposium on Aerosol–Cloud–Climate Interactions, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

*Seventh Conference on Environment and Health, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*Sixth Conference on Transition of Research to Operations, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

*12th Annual Symposium on New Generation Operational Environmental Satellite Systems, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*12th IMPCACTS: Major Weather Events and Societal Impacts of 2015, 12 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

*11th Conference on Artificial and Computational Intelligence and its Applications to the Environmental Sciences, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*10th Annual CCM Forum, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: Feb. 2015

*Sixth Conference on Transition of Research to Operations, 10–14 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

*12th IMPCACTS: Major Weather Events and Societal Impacts of 2015, 12 January, New Orleans, Louisiana
Abstract deadline: 3 August 2015
Preregistration deadline: 1 December 2015
Manuscript deadline: 12 February 2016
Initial announcement published: March 2015

*An exhibit program will be held at this meeting.
Student Travel Grants are available for senior undergraduate and graduate students to attend AMS meetings held in the United States and Canada. The travel grants are available only to members, including student members, of the AMS.

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

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

For more information and to complete an application form, please visit the AMS website at www.ametsoc.org.
The confluence of wireless sensors systems, massive use of smart phones, and the resulting rapid advances in commercial RF devices has led to the emergence of a new generation of low-cost but highly advanced phased-array antenna technologies. Features such as agile/multiple beams, low profiles, and high reliability offer wide-ranging possibilities for military and civil applications. Potential phased-array applications in weather radar, agile beams enable enhanced temporal resolution, are key features for sampling large volumes of atmospheric phenomena where the life cycle is less than 30 minutes. Current advances in semiconductor technologies provide better integration and power density; as a result, smaller and more lightweight antennas can be installed on the sides of buildings, communication towers, and space and airborne platforms. There is however a significant gap in the understanding of the challenges associated with the adoption of phased array technology for weather applications. There remain many fundamental questions surrounding how to relate traditional weather radar performance to equivalent metrics and operation on a phased array, including those revolving around appropriate scanning strategies, multi-polarization and antenna patterns, thermal management, calibration, and both initial and life cycle costs. In the last decade, researchers and engineers have been focused on getting a better understanding of these questions, and have also worked toward engineering solutions to the emerging challenges. This is particularly true for polarimetric antenna patterns, which are significantly more complicated in phased arrays. Additionally, an understanding of the differences between phased array and dish main-beam characteristics is important for reusing developed algorithms for conventional and operational weather radars.

This short course will cover an introduction to phased array antennas for atmospheric research, short presentations of existing phased array radars (ground-based, airborne, and spaceborne), and provide an overview of applications in atmospheric research. The main focus is to introduce the most important challenges in the use of phased array antennas for atmospheric research: Dual polarization and calibration. A discussion of practical design consideration for dual-polarized active phased array will be included, followed by a live demonstration of antenna performance in an anechoic chamber.

The course format consists of one day of lectures followed by two hours of hands-on laboratory session with exercises that can be completed any day of lectures followed by two hours of hands-on laboratory session with exercises that can be completed any day of lectures followed by two hours of hands-on laboratory session with exercises that can be completed any day of lectures followed by two hours of hands-on laboratory session with exercises that can be completed any day of lectures followed by two hours of hands-on laboratory session with exercises that can be completed. The instructors for the course are Professors Jorge Salazar and Caleb Fulton, University of Oklahoma at Norman.

A luncheon and two coffee breaks will be provided during the short course. Access to the Internet will be available.

For more information please contact Jorge L. Salazar or Caleb Fulton at University of Oklahoma at Norman, 3190 Monitor Avenue, Norman, OK 73072 (tel: 405-325-6499/4278; e-mails: salazar@ou.edu, fulton@ou.edu. (8/15)
data using the IPython notebook; 2. An introduction to Py-ART including reading, plotting, basic manipulation and saving radar data; 3. Intermediate usage including retrievals and tools built on top of Py-ART and other Python radar applications.

The instructor for the course is Dr. Scott Collis of Argonne National Laboratory. He will be joined by Drs. Jonathan Helmus, Nick Guy, Timothy Lang, Joseph Hardin, and Marcus van Lier-Walqui.

A luncheon will be provided during the short course. Access to your own laptop with at least 2 GB of memory and 1 GB of free space will be essential for the course. Attendees will receive a thumb drive with all materials, software, and data.

For more information please contact Scott Collis at Argonne National Laboratory, Building 240, 9200 S Cass Ave, Argonne, IL 60439 (tel: 630-252-0550; e-mail: scollis@anl.gov). (8/15)

ANNOUNCEMENT
AMS Short Course on Radar Aeroecology, 13 September 2015, Norman, Oklahoma

The AMS Short Course on Radar Aeroecology will be held on the 13th of September 2015 in Norman, Oklahoma, preceding the 37th Conference on Radar Meteorology. Preliminary programs, registration, hotel, and general information will be posted on the AMS Web site (www.ametsoc.org/meet/fainst/201537radar.html) by mid-July 2015.

Weather radar networks—such as NEXRAD—regularly collect data from biological scatter (bioscatter). Although these data are typically filtered out as non-meteorological signals for weather applications, they provide a valuable means of exploring the multitude of volant animals in the airspace. By establishing stronger linkages between the weather and biological communities, data from bioscatter could conceivably be processed and distributed as higher-order products in the same way that radar data from weather can be used to produce rainfall rates, cloud depth, liquid water content, and so forth. Moreover, by better understanding the biological signal, researchers can more effectively identify and remove bioscatter from weather data. The rich data set has yet to be fully explored. This short course aims to help bridge the gap between meteorologists and biologists so they can mutually explore the value of bioscatter data.

The goal of the course is introduce the concept of aeroecology to the broader meteorological community, examine the scattering properties of airborne biological entities (birds, bats, and arthropods), and examine how weather radar can be used to provide meaningful data pertaining to the distribution and movement of these animals, highlighting the weather–biological interface.

The course format consists of introductory lectures followed by hands-on laboratory sessions with exercises using data and software to be provided. The instructor for the course is Prof. Phillip Chilson, University of Oklahoma. He will be joined by: Prof. Jeffrey Kelly (University of Oklahoma), Prof. Jeffrey Buler (University of Delaware), Dr. Valery Melnikov (NOAA NSSL), and Mr. Kyle Horton (University of Oklahoma).

A coffee break will be provided during the half-day short course. The participants are encouraged to use their own laptops for the course but some computer work stations will be provided. Internet access will be available for this course.

For more information please contact P. Chilson at the University of Oklahoma, 120 David L. Boren Blvd., Norman, Oklahoma (tel: 405-325-5095, e-mail: chilson@ou.edu) (8/15)

ANNOUNCEMENT
AMS Short Course on CM- and MM-Wavelength Radar Applications, 13 September 2015, Norman, Oklahoma

The AMS Short Course on CM- and MM-Wavelength Radar Applications...
will be held on 13 September 2015 preceding the 37th AMS Conference on Radar Meteorology in Norman, Oklahoma. Preliminary programs, registration, hotel, and general information will be posted on the AMS Web site (www.ametsoc.org/meet/fainst/201537radar.html) in early July 2015.

The number of millimeter-wavelength (cloud) radars and the range of their applications have increased dramatically the last two decades. Yet, there is a gap in comprehensive millimeter-wavelength radar course material in most undergraduate/graduate programs in the United States and other countries that offer radar meteorology courses and research. Another knowledge gap exists in the synergy of cm- and mm-wavelength radars for cloud and precipitation research. Research groups tend to focus on either weather or cloud radar systems and ignore the benefits of having coordinated measurements from both cm- and mm-wavelength radars. This course will explore these benefits using cm- and mm-wavelength observations from the U.S. Department of Energy ARM (www.arm.gov) sites.

The goal of the course is to introduce mm-wavelength radars to the broader community, discuss the theory and applications of radar Doppler spectra and demonstrate examples where cm- and mm-wavelength work together to provide a more complete, holistic view of the water cycle.

The course format consists of a few introductory lectures followed by several hours of hands-on laboratory sessions with exercises using data and software that will distributed online from the course coordinator website in advance of the course. The instructor for the course is Prof. Pavlos Kollias, McGill University. He will be joined by Edward Luke (Brookhaven National Laboratory), Dr. Stefan Kneifel (University of Cologne), Prof. Alessandro Battaglia (University of Leicester) and Dr. Frederic Tridon (University of Leicester).

A luncheon will be provided during the short course. The participants are expected to use their own laptops for the course. Internet access will be available for this course.

For more information please contact P. Kollias at McGill University, Department of Atmospheric and Oceanic Sciences, Burnside Hall Room 945, 805 Sherbrooke Street West, Montreal H3A 0B9, QC, Canada (tel: 514-398-1500, e-mail: Pavlos.kollias@mcgill.ca) (8/15)
Eyewitness: Evolution of the Atmospheric Sciences describes how the atmospheric sciences were transformed in the span of the author’s professional career from its origins in primitive weather forecasting to its current focus on numerical modeling of environmental change. It describes the author’s observations of persons, events, and institutions beginning with graduate study during the Second World War and moving on to continuing expansion of the atmospheric sciences and technologies, through development of a major university department, development of new scientific and professional institutions, and to the role that the science of the atmosphere now plays in climate change and other issues of social and political policy.

Eyewitness: Evolution of the Atmospheric Sciences
Order online: www.ametsoc.org/amsbookstore
or see the order form at the back of this issue.

About the Author
Robert G. Fleagle earned degrees in physics and meteorology at The Johns Hopkins University and New York University and began his professional career in 1948 at the University of Washington (UW). His research has focused on the structure of midlatitude cyclones, the physics and structure of the surface boundary layer, and processes of air–sea interaction. He is the author of about 100 papers published in scientific journals and of books on atmospheric physics and global environmental change. Applications of science to social and political policy have been important motivations for his career and have occupied his attention increasingly as the decades passed.

Fleagle participated at close range in the beginnings and growth of a major university department and of the University Corporation for Atmospheric Research (UCAR). In 1963 and 1964 he served as a staff specialist in the Office of Science and Technology, Executive Office of the President, and in 1977–78 he served as consultant to the National Oceanic and Atmospheric Administration. He has held many administrative posts including chairman of the UW Department of Atmospheric Sciences (1967–77), chairman of the National Academy of Sciences Committee on Atmospheric Sciences (1969–73),
CLIMATE

The Thinking Person’s Guide to Climate Change
ROBERT HENSON
This fully updated and expanded revision of The Rough Guide to Climate Change combines years of data with recent research. It is the most comprehensive overview of climate science, acknowledging controversies but standing strong in its stance that the climate is changing—and something needs to be done.

Climate Conundrums: What the Climate Debate Reveals about Us
WILLIAM B. GAIL
This is a journey through how we think, individually and collectively, about humanity’s relationship with nature, and more. Can we make nature better? Could science and religion reconcile? Gail’s insights on such issues help us better understand who we are and find a way forward.

Living on the Real World: How Thinking and Acting Like Meteorologists Will Help Save the Planet
WILLIAM H. HOOKE
Meteorologists focus on small bits of information while using frequent collaboration to make decisions. With climate change a reality, William H. Hooke suggests we look to the way meteorologists operate as a model for how we can solve the 21st century’s most urgent environmental problems.

GUIDES

TOBY CARLSON, PAUL KNIGHT, AND CELIA WYKOFF
With help from Penn State experts, start at the beginning and go deep. This primer, intended for both serious enthusiasts and new meteorology students, will leave you with both refined observation skills and an understanding of the complex science behind the weather: the ingredients for making reliable predictions of your own. It connects fundamental meteorological concepts with the processes that shape weather patterns, and will make an expert of any dedicated reader.

Eloquent Science: A Practical Guide to Becoming a Better Writer, Speaker, and Atmospheric Scientist
DAVID M. SCHULTZ
The ultimate communications manual for undergraduate and graduate students as well as researchers in the atmospheric sciences and their intersecting disciplines.

TEXTBOOK

Midlatitude Synoptic Meteorology: Dynamics, Analysis, and Forecasting
GARY LACKMANN
This textbook links theoretical concepts to modern technology, facilitating meaningful application of concepts, theories, and techniques using real data.
© 2011, PAPERBACK, 360 PAGES, ISBN 978-1-878220-10-3 LIST $100 MEMBER $75 STUDENT MEMB. $65

Midlatitude Synoptic Meteorology Teaching CD
More than 1,000 PowerPoint Slides.
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A Scientific Peak: How Boulder Became a World Center for Space and Atmospheric Science

JOSEPH P. BASSI

How did big science come to Boulder, Colorado? Joe Bassi introduces us to the characters, including Harvard sun–Earth researcher Walter Orr Roberts, and the unexpected brew of politics, passion, and sheer luck that during the Cold War era transformed this “Scientific Siberia” to home of NCAR and NOAA.
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.

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### 2016 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 2016 for the awards that follow, unless stated otherwise. The nominees for awards remain on the committee's active list for three years.

#### ATMOSPHERIC RESEARCH AWARDS COMMITTEE
- The Carl-Gustaf Rossby Research Medal
- The Jule G. Charney Award
- The Verner E. Suomi Award*
- The Remote Sensing Prize (biennial)
- The Clarence Leroy Meisinger Award
- The Henry G. Houghton Award

#### OCEANOGRAPHIC RESEARCH AWARDS COMMITTEE
- The Sverdrup Gold Medal
- The Henry Stommel Research Award
- The Verner E. Suomi Award*
- The Nicholas P. Fofonoff Award

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

#### AWARDS OVERSIGHT COMMITTEE
- The Charles Franklin Brooks Award for Outstanding Services to the Society
- The Cleveland Abbe Award for Distinguished Service to the Atmospheric Sciences by an Individual
- The Joanne Simpson Mentorship Award
- The Award for Outstanding Services to Meteorology by a Corporation Special Awards

#### EDUCATION AND HUMAN RESOURCES COMMISSION
- The Louis J. Battan Author’s Award (Adult and K–12)
- The Charles E. Anderson Award
- The Teaching Excellence Award
- Distinguished Science Journalism in the Atmospheric and Related Sciences

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

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

#### LOCAL CHAPTER AFFAIRS COMMITTEE
- Local Chapter of the Year Award
  (nomination form available online at www.ametsoc.org/amschaps/index.html)

* Recommended by the Atmospheric Research Awards Committee in even-numbered years and by the Oceanographic Research Awards Committee in odd-numbered years.
2016 AWARDS COMMITTEES

SCIENTIFIC AND TECHNOLOGICAL ACTIVITIES COMMISSION
The Charles L. Mitchell Award
The Award for Exceptional Specific Prediction
The Francis W. Reichelderfer Award
The Helmut E. Landsberg Award
The Award for Outstanding Achievement in Biometeorology
• LECTURERS
  Robert E. Horton Lecturer in Hydrology
  Bernhard Haurwitz Memorial Lecturer
  Walter Orr Roberts Lecturer
• PAPER
  Banner I. Miller
• STUDENT PAPERS
  Robert Leviton Student Prize
  Max A. Eaton Student Prize
  Spiros G. Geotis Student Prize
  Peter V. Hobbs Student Prize
• NAMED SYMPOSIA
  Section E, of the Policy, Guidelines, and Procedures for Awards and Lectureships provides the Policy on Named Conferences/Symposia and Special Issues of AMS Journals (full policy description available at www.ametsoc.org/awards):

Recognition of scientists in the fields served by the AMS, living or deceased, in the form of a named conference or symposium or a named special issue of one of the Society’s journals is an honor reserved for only the most outstanding of our colleagues. It should be awarded only to those individuals who are completing a career, or who have recently died having completed a career, of significant achievements in their field and whose contributions would make them worthy of consideration for Honorary Member of the AMS…

2016 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 2016. A list of Fellows and the process for submitting nominations are on the AMS website (www.ametsoc.org/awards).

2016 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 97th Annual Meeting (January 2017) 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 2016 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 2016; 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.

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Dartmouth College Baker Library

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

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Republic of Korea Air Force, Headquarters
South African Weather Service
St. Louis University, Dept. of Earth & Atmospheric Sciences
Swedish Meteorological & Hydrological Institute
U.K. National Meteorological Library
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Zentralanstalt fur Meteorologie und Geodynamik

*ADD: Indian Institute of Technology Bhubaneswar (new member)

Color indicates new or reinstated member
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Lockheed Martin Corporation*
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NOAA’s National Weather Service

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Harris Corporation
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Karen Hauschild Friday Endowed Scholarship
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The Jerry C. Glover Scholarship
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Richard and Helen Hagemeyer Scholarship
John R. Hope Endowed Scholarship in Atmospheric Sciences
David S. Johnson Endowed Scholarship
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Dr. Yoram Kaufman Scholarship
Carl W. Kreitzberg Endowed Scholarship
Ethan and Allan Murphy Endowed Memorial Scholarship
The Naval Weather Service Association Scholarship Award
K. Vic Ooyama Endowed Scholarship
The Orville Family Endowed Scholarship in Meteorology
The Ken Reeves Scholarship
Michael J. Roberts, Jr. Scholarship
Guillermo Salazar Rodriguez Undergraduate Scholarship
Mark J. Schroeder Endowed Scholarship in Meteorology

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<tr>
<th>Company</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belfort Instruments</td>
<td>c4</td>
</tr>
<tr>
<td>EKO Instruments</td>
<td>1226</td>
</tr>
<tr>
<td>Environmental Research Services</td>
<td>1225</td>
</tr>
<tr>
<td>Geonor Inc.</td>
<td>1222</td>
</tr>
<tr>
<td>Kipp &amp; Zonen (USA) Inc.</td>
<td>c2</td>
</tr>
<tr>
<td>LI-COR</td>
<td>c3</td>
</tr>
<tr>
<td>R. M. Young Company</td>
<td>1223</td>
</tr>
<tr>
<td>Yankee Environmental Systems, Inc.</td>
<td>1213</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive Governance and Climate Change</td>
<td>1367</td>
</tr>
<tr>
<td>AMS Books</td>
<td>1232, 1418–1419, 1425</td>
</tr>
<tr>
<td>AMS eBooks</td>
<td>1256</td>
</tr>
<tr>
<td>AMS Merchandise Catalog</td>
<td>1380</td>
</tr>
<tr>
<td>AMS Journals—Mobile Editions</td>
<td>1350</td>
</tr>
<tr>
<td>AMS Online Bookstore</td>
<td>1280</td>
</tr>
<tr>
<td>The AMS Weather Book: The Ultimate Guide to America’s Weather</td>
<td>1408</td>
</tr>
<tr>
<td>BAMS Digital Edition</td>
<td>1231</td>
</tr>
<tr>
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<td>1416</td>
</tr>
<tr>
<td>Eyewitness: Evolution of the Atmospheric Sciences</td>
<td>1417</td>
</tr>
<tr>
<td>Father Benito Viñes: The 19th-Century Life and Contributions of a Cuban Hurricane Observer and Scientist</td>
<td>1392</td>
</tr>
<tr>
<td>A Half Century of Progress in Meteorology: A Tribute to Richard Reed, MM No. 53</td>
<td>1368</td>
</tr>
<tr>
<td>The Life Cycles of Extratropical Cyclones</td>
<td>1430</td>
</tr>
<tr>
<td>Living on the Real World: How Thinking and Acting Like Meteorologists Will Help Save the Planet</td>
<td>1309</td>
</tr>
<tr>
<td>Midlatitude Synoptic Meteorology</td>
<td>1411</td>
</tr>
<tr>
<td>Online Career Center</td>
<td>1431</td>
</tr>
<tr>
<td>Online Glossary of Meteorology</td>
<td>1220</td>
</tr>
<tr>
<td>Online Membership Directory</td>
<td>1424</td>
</tr>
<tr>
<td>Radar and Atmospheric Science: A Collection of Essays in Honor of David Atlas, MM No. 52</td>
<td>1310</td>
</tr>
<tr>
<td>Taken by Storm, 1938: The Societal and Meteorological History of the Great New England Hurricane</td>
<td>1219</td>
</tr>
<tr>
<td>The Thinking Person’s Guide to Climate Change</td>
<td>1349</td>
</tr>
<tr>
<td>Weather on the Air: A History of Broadcast Meteorology</td>
<td>1255</td>
</tr>
<tr>
<td>Weatherwise</td>
<td>1242</td>
</tr>
</tbody>
</table>

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</tr>
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