MULTIFUNCTIONAL MESOSCALE OBSERVING NETWORKS

BY WALTER F. DABBERDT, THOMAS W. SCHLATTER, FREDERICK H. CARR, ELBERT W. JOE FRIDAY,
DAVID JORGENSEN, STEVEN KOCH, MARIA PIRONE, F. MARTIN RALPH, JUANZHEN SUN,
PATRICK WELSH, JAMES W. WILSON, AND XIAOLEI ZOU

The mesoscale measurement challenge can best be met by an integrated approach that considers an end-to-end solution.

The U.S. Weather Research Program (USWRP) sponsored a community workshop on the design and development of multifunctional mesoscale observing networks in support of integrated forecasting systems, on 8–10 December 2003 at the National Center for Atmospheric Research in Boulder, Colorado. The workshop goals were to identify challenges, needs, and opportunities involved in developing improved, economically viable, integrated atmospheric mesoscale observing, modeling, and information-delivery systems. Recommendations were sought for improved mesoscale observing networks that recognize the needs of users, modelers, and forecasters.

Background. The development and delivery of accurate, reliable, and useful mesoscale atmospheric forecasts present special needs, challenges, and opportunities that currently are not being met in a consistent and uniform way. As the resolution of atmospheric forecast models has increased, there has been a corresponding, but smaller, increase in forecast skill and utility to end users. The full benefit of enhanced forecast model resolution has not been and will not

AFFILIATIONS: DABBERDT—Vaisala, Inc., Boulder, Colorado; SCHLATTER AND KOCH—National Oceanic and Atmospheric Administration/Oceanic and Atmospheric Research/Forecast Systems Laboratory, Boulder, Colorado; CARR AND FRIDAY—University of Oklahoma, Norman, Oklahoma; JORGENSEN—National Oceanic and Atmospheric Administration/Oceanic and Atmospheric Research/National Severe Storms Laboratory, Boulder, Colorado; PIRONE—Atmospheric and Environmental Research, Inc., Lexington, Massachusetts; RALPH—National Oceanic and Atmospheric Administration/Oceanic and Atmospheric Research/Environmental Technology Laboratory, Boulder, Colorado; SUN AND WILSON—National Center for Atmospheric Research, Boulder, Colorado; WELSH—NOAA/National Weather Service, Jacksonville, Florida; ZOU—Florida State University, Tallahassee, Florida

CORRESPONDING AUTHOR: Walter F. Dabberdt, Vaisala, Inc., P.O. Box 3659, Boulder, CO 80305-3000
E-mail: walter.dabberdt@vaisala.com

DOI:10.1175/BAMS-86-7-961

In final form 14 March 2005

©2005 American Meteorological Society

be realized without commensurate improvements in high-resolution meteorological observations, as well as improvements in data assimilation, model physics, parameterizations, and user-specific analyses and forecast products. There are clear, albeit limited, examples that demonstrate the value and viability of integrated mesoscale observing and forecasting systems. There is also an emerging consensus among the observational, modeling, and forecast communities that carefully designed, integrated three-dimensional mesoscale networks will yield markedly improved short-range forecasts. These forecasts will significantly benefit users in many communities, including those of severe weather (public safety), flash flooding, water management, energy production and management, agriculture, air quality, homeland security, public health, and more.

General workshop charge. The general charge to the workshop was to identify the challenges, needs, and opportunities involved in developing improved, economically viable, integrated atmospheric mesoscale observing, modeling, and information-delivery systems. *Improved* mesoscale observing networks are defined as those that yield analyses and forecasts of the atmospheric physical and chemical state—including precipitation, ground condition, and runoff—that are more precise, accurate, timely, and user relevant than today's products. *Economically viable* systems are defined as systems that produce analysis and forecast products for which user groups have both real needs and a willingness to bear the associated costs. In this context, user groups include federal, state, and local agencies; private weather information providers; and end-user groups.

Work group themes and participants. The workshop comprised four work groups, each dealing with a complementary aspect of the challenge. The nowcasting work group was charged with summarizing very short range forecasting research needs that were identified in previous studies and workshops. They were asked to identify the observing needs required to support research aimed at developing, testing, and transitioning to operations improved nowcasting systems for severe weather (both cold and warm season), acute air quality, hydrology, chemical emergency response, and other applications. The advanced modeling and data assimilation work group was charged with identifying the observing needs that are required to support research aimed at developing, testing, and transitioning to operations improved short-to-medium-range data assimilation and modeling systems for the same conditions and applications as the nowcasting group. The test beds work group was charged with identifying ways in which demonstration mesoscale test beds could be created to test and evaluate the technical, scientific, and economic viability of the test bed concept and to identify ways in which they could be scaled up to the national level. The charge to the implementation work group was to identify potential user groups and their particular needs and requirements. They were asked to identify the scope and nature of public–private–academic partnerships that might be viable avenues for implementing the mesoscale networks of the future, as well as the different roles that the three sectors might assume.

Workshop participation was well balanced among the public, private, and academic communities, with 41 participants from the public sector (37 domestic plus 4 international), 52 from the academic sector (49 plus 3), and 29 from the private sector (25 plus 4). Participants, invited speakers, and the workshop agenda are listed at the USWRP Web site (information online at http://box.mmm.ucar.edu/uswrp/recent_meetings/recent_meetings.html).

MESOSCALE OBSERVATIONS FOR NOWCASTING.

Focus. Nowcasting is forecasting with local detail, by any method, over a period from the present to a few hours ahead; this includes a detailed description of the present weather. Nowcasting is a blend of extrapolation techniques, statistical techniques, heuristic techniques, and numerical methods. Heuristic techniques are defined as forecast rules based on experimentation, numerical simulations, theory, and forecaster rules of thumb.

The work group on nowcasting[1] defined the following objectives:

- identify research and observational needs required to improve nowcasting,
- identify candidate observing systems and methods for designing observing networks, and
- consider the use of test beds as a mechanism for transferring methods and technologies from research to operations.

To bound the discussions, the work group focused on instrumentation needs for the 0–6-h forecast period (nowcast period) with emphasis on high-impact weather, such as heavy precipitation, high winds, pre-

---

[1] Nowcasting work group coleaders were P. Welsh and J. Wilson.

cipitation type, icing, lightning, hail, and tornadoes. The work group also considered poor air quality and the dispersion of toxic materials, which are items not traditionally associated with high-impact weather. In discussing instrumentation needs, the work group wanted to embrace all 0–6-h nowcasting techniques, including extrapolation, probabilistic information, and numerical computation (including simple data assimilation and models—a direction in which nowcasting is headed).

Scientific Challenges in Nowcasting. CONVECTIVE WEATHER. Basic research is required to improve the understanding of factors governing the evolution of convective storms and associated weather hazards. This research will require high-resolution observations of wind, temperature, moisture, precipitation, clouds, and total lightning in order to better understand the physical processes that generate convection. The high-resolution observation of water vapor has been identified by a variety of national study groups (e.g., Dabberdt and Schlatter 1996) as one of the most critical missing parameters. Key scientific challenges include the need for

- a more realistic simulation of convective processes within numerical models,
- an improved understanding of factors controlling the timing and characteristics of convective downdrafts and associated gust fronts from individual storms, and
- an improved understanding of processes that initiate convection, including those forcing elevated convection.

WINTER WEATHER. The primary winter weather nowcasting challenges are precipitation type, snow depth, ground temperature, liquid equivalent, start and stop times of precipitation, icing, and freezes and frost when and where they are not normally expected. Because winter events are often not forced from the boundary layer, high-resolution information from the entire troposphere is required to understand the dynamical mechanisms generating the precipitation patterns. In this context, the USWRPs Prospectus Development Team (PDT)-10 (Dabberdt et al. 2000) identified the following six specific, observationally oriented research needs pertaining to winter storms:

- refinement of radar precipitation estimates in wintertime regimes,
- improvement of the prediction of mixed water–ice phase precipitation on scales < 10 km,
- improvement of the quantitative and area forecasts of frozen/freezing precipitation on scales of 1–12 h and 10 km,
- differentiation and characterization of precipitation structures conducive to supporting convective snowfall events,
- exploration of the value of GPS- and radar-based estimates of integrated precipitable water vapor and refractive index profiles at scales of < 3 h and 0–100 km, and
- full exploration and exploitation of meteorological measurements from commercial aircraft.

Enhancements to existing systems to support improved nowcasting. NATIONAL SURFACE MESCOSCALE NETWORK. The work group agreed that establishing a national mesoscale network of surface stations to complement the Weather Surveillance Radar-1988 Doppler (WSR-88D) network should be the first step toward improving convective storm nowcasts. The spacing of these stations should be 25 km in flat terrain, 10 km along coastal regions, and less than 25 km in mountainous terrain, depending on the situation. In coastal regions the stations should be integrated with the coastal observing network. In urban areas the station spacing will often need to be less (sometimes much less) than 10 km. The reporting frequency of the stations should be every 5 min or less.

The basic surface station should record wind, temperature, humidity, pressure, and precipitation amount. Where snow occurs, the base station should also measure the liquid equivalent and snow depth. Depending on user needs, additional parameters could be measured, for example, precipitation type, soil temperature and moisture, radiative flux, ceiling, and visibility. A station spacing of 10 km would require roughly 100,000 stations nationally, but 25-km spacing would call for only 16,000 stations. The National Oceanic and Atmospheric Administration (NOAA) Forecast Systems Laboratory (FSL) currently collects about 13,000 surface reports hourly from over 30 different sources (see information online at www-frd.fsl.noaa.gov/mesonet/) (Miller and Barth 2003). Although that is close to the recommended minimum number of hourly reports for a national "flat terrain" network, the spatial distribution, temporal frequency, parameters measured, and quality of these reports are not uniform. Nonetheless, the number indicates that a national network as envisioned is not out of the question. The National Weather Service (NWS) has committed to modernize the National Cooperative Observer Program network (information online at www.nws.noaa.gov/om/coop/reference/PDP4COOP.pdf), which would result in thousands of new automated stations reporting temperature and precipitation in real time. Every effort should be made to include the other variables indicated above; options for accomplishing this are explored in the "Implementation aspects: Users, user needs, and partnership opportunities for the public–private–academic sectors" section. All stations should meet set standards for data quality; in any case, however, quality assurance procedures must be instituted to flag bad data.

POLARIMETRIC RADAR. A national network of polarimetric radars would prove to be tremendously valuable, primarily because these radars provide information on hydrometeor type. That means, for example, that forecasters could distinguish either the rain–snow line in winter or tell the difference between very heavy rain and large hail in a summer thunderstorm. If hydrometeor type is known, precipitation estimates are much improved, and models that predict concentrations of various species of hydrometeor can assimilate this information.

RADAR COVERAGE IN THE BOUNDARY LAYER. The national network of WSR-88D radars is useful at mapping precipitation and indicating the severity of convective storms, particularly east of the Rocky Mountains. However, the average spacing between radars precludes sampling of nearly 70% of the boundary layer. Boundary layer sampling is critical for accurate estimates of rainfall, detection of powerful storm outflows or rotary motion at low levels, identification of low-level convergence that triggers thunderstorms, and coverage of areas blocked by terrain. Other radars could be integrated into the WSR-88D network to improve the situation, such as the 45 Terminal Doppler Weather Radars (TDWRs), which are operated by the Federal Aviation Administration (FAA), and more than 100 private radars, many operated by television stations. A recent study, "Weather radar technology beyond NEXRAD" (National Research Council 2000), has already recommended that ways be found to integrate these diverse radars into a national network to improve coverage. The same NRC study also recommended that a network of low-power, short-range radars be considered to improve surveillance of the boundary layer. A consortium of universities supported by the National Science Foundation (NSF), called the Collaborative Adaptive Sensing of Atmosphere (CASA; information online at http://casa.umass.edu) program, is developing and testing means to use a network of very closely spaced, inexpensive X-band radars to improve coverage of the boundary layer. Finally, the National Severe Storms Laboratory is testing the large AN/SPY-1A phased-array radar, previously deployed on U.S. Navy ships, to demonstrate the value of being able to scan severe storms at least 5 times faster than today's WSR-88D radars.

PROFILING THE BOUNDARY LAYER. The importance of boundary layer measurements in mesoscale forecasting during all four seasons can hardly be overemphasized. Nowcasts of convective storm initiation and intensity are greatly influenced by the height and strength of the inversion, the convective available potential energy (CAPE), and convective inhibition (CIN). However, measurements of these parameters suffer from poor time and space resolution.

Among the systems that are capable of sampling the boundary layer are WSR-88D radars, commercial aircraft on ascent and descent [Meteorological Data Collection and Reporting System (MDCRS)], rawinsondes, Radio Acoustic Sounding Systems (RASSs), infrared radiometric soundings from the Geostationary Operational Environmental Satellite (GOES), wind profilers, sodars, and lidars. The WSR-88D radars have a limited ability to sample the clear-air boundary layer, especially in winter; the vertical resolution of most aircraft soundings in the boundary layer is woefully inadequate; radiosonde reports are limited to twice a day, and miss many important mesoscale developments; and RASS, though it delivers boundary layer profiles of virtual temperature, has noise pollution problems and a limited vertical reach (≤ 1 km when used with boundary layer profilers, 3–4 km when used with full tropospheric profilers). Infrared soundings from GOES, particularly at 10-km resolution in cloud-free areas, show promise for mapping CAPE and CIN fields (Wade et a1. 2003). Wind profilers—the 35 that comprise the NOAA Profiler Network in the central United States, and the more than 60 that are part of the Cooperative Agency Profiler (CAP) network, concentrated mostly near larger cities along the U.S. coastlines—report every 6 min and provide valuable diagnostic information for many nowcasting applications. The NWS is considering a national expansion of the profiling network as part of a future Integrated Upper Air Observing System. The work group strongly supports this initiative.

Research instruments used mostly in field projects today may greatly improve boundary layer surveillance in the future. Ground-based lidars sample aerosol concentrations or infer moisture profiles. The Atmospheric Emitted Radiance Interferometer

(AERI) measures the absolute infrared spectral radiance of the sky directly above the instrument. Every 10 min, AERI can calculate profiles of temperature and humidity, although it cannot see through clouds. The Atmospheric Infrared Sounder (AIRS), recently launched on the National Aeronautics and Space Administration's (NASA's) *Aqua* satellite, is providing more detailed temperature and moisture soundings in cloud-free air than were previously possible. AIRS takes measurements in thousands of channels instead of two dozen or so—the capability of most of the radiometers currently in space. Research is required to examine the utility of these products for characterization of the boundary layer.

LIGHTNING DETECTION. Information on total lightning would be a valuable complement to WSR-88D radar data and surface mesoscale networks, especially in mountainous areas where radar coverage is limited. Total lightning includes not only cloud-to-ground strokes, for which there is already a National Lightning Detection Network (Orville 1991), but also within-cloud, cloud-to-cloud, and cloud-to-air strokes. Satellites in low orbits are already used to estimate total flash rates, but they cannot see the contiguous United States all at one time. A lightning detector that is proposed for future GOES satellites might solve the coverage problem. Several existing ground-based specialized Lightning Mapping Arrays not only monitor each flash, but can also locate the branching channels of a flash in three dimensions. How total lightning data can be used to refine severe weather warnings when minutes count and to improve nowcasts, particularly in the first hour, is the subject of active research (e.g., see information online at http://weather.msfc.nasa.gov/sport/2004_latest_agenda.html).

Gaps in existing observations and data analyses that hamper nowcasting. LOW-LEVEL MOISTURE. The distribution and transport of water vapor have a large impact on storm initiation, growth, and severity. Low-level moisture, particularly its vertical distribution and transport, is very poorly measured. Several national study groups have previously identified water vapor measurements as being critical to improving storm and quantitative precipitation forecasts (see, e.g., recommendation 4 in Emanuel et al. 1995). A large research field program [the International H2O Project (IHOP); see additional information online at www.atd.ucar.edu/dir_off/projects/2002/IHOP.html] was conducted in 2002 to obtain improved water vapor measurements. Of particular note are the recent IHOP findings that radar refractivity measurements from S-band radars can provide a near-surface field of water vapor measurements within the radar range at which ground targets are typically observed (out to 40–60 km). However, these findings should be further confirmed in nowcasting field projects and test beds.

The nowcasting group asserted that accurate relative humidity (RH) measurements from radiosondes are essential for nowcasting purposes. The NWS should not consider a reduction in the quality of radiosonde RH data (e.g., avoiding the use of on-site sensor conditioning) and should not reduce the number of radiosonde sites until a proven substitute can be found for moisture soundings with a high vertical resolution.

SHARP GRADIENTS IN STATE VARIABLES. Sharp gradients in state variables, particularly those associated with convergence lines, are crucial to convective storm and storm-severity nowcasts, but there is no standard way to portray them. A national map of boundary layer convergence lines would be particularly useful for improving convective storm nowcasting. This map should span spatial scales from synoptic fronts down to individual gust fronts and show their characteristics, such as magnitude of convergence and gradients of temperature, pressure, and moisture. These features should be defined by integrating information from the following instruments: radar, satellite, surface mesoscale networks, ground-based GPS, automated aircraft reports (MDCRS), Automated Surface Observing System (ASOS), and instrumented vehicles (trains, cars, trucks, and buses).

BOUNDARY LAYERS IN DATA ANALYSIS AND ASSIMILATION SYSTEMS. National-scale data analysis and assimilation systems do not fully capitalize on surface and boundary layer observations, and are, therefore, of a limited value for nowcasting. The methods that human forecasters need for nowcasting applications (e.g., the national convergence-line analysis) may require very different approaches from those that are considered optimal for initializing numerical weather prediction models. Analyses of boundary layer parameters are useful for more than just initializing models. For example, high-resolution wind analyses are useful for nowcasts of air quality, toxic dispersion, and thunderstorms.

STATE VARIABLES ABOVE THE BOUNDARY LAYER. High-resolution three-dimensional observations of state variables above the boundary layer are currently insufficient. Such observations are essential for nowcasting elevated convection and winter precipitation (icing, freezing rain, sleet, and mixed precipitation). Currently there is no observational capability to fill this gap. Possible solutions to this problem are frequency-modulated–continuous-wave (FM–CW) and L-band (15–30-cm wavelength) radars; the latter are capable of inferring winds in clear air from Bragg scattering, which results from highly localized variations in temperature and humidity. Through data assimilation, efforts should also be made to retrieve the state variables from the high-resolution observations that are already available—WSR-88D and other radar data, and horizontal gradient data from satellites.

Rapidly deployable wildfire sensors. Nowcasting for wildfires and other singular events requires sensors that can be rapidly deployed. Though the U.S. Forest Service has a number of automated remote surface stations, many more are needed in the immediate vicinity of a fire. Mobile profilers or scanning radars can be used to define the wind field in the vicinity of the fire, thus, aiding on-site meteorologists to anticipate the rate of spread, and researchers to investigate wind–fire relationships. Dropwindsondes deployed from firefighting and reconnaissance aircraft could also provide valuable profiles of wind and state variables.

Coastal buoys. The present number of coastal buoys is very limited. A spacing of about 100 km is recommended. Observations of the standard variables are needed, as are measurements of wave height and direction, and depth profiles of salinity and temperature. Doppler current profilers and buoy-mounted atmospheric profilers are also desirable.

Observation requirements for homeland security. Homeland security requires observational scales of hundreds of meters to support high-resolution dispersion models. This has been thoroughly discussed in a recent report titled "Tracking and predicting the atmospheric dispersion of hazardous material releases" (National Research Council 2003a). Meteorological observing systems needed for emergency-response dispersion modeling would also support many other nonemergency applications.

Testbeds for nowcasting. A nowcasting test bed is the preferred vehicle to accelerate the infusion of science and technology into operations, to evaluate new techniques and products of benefit to end users, to train forecasters, and to serve as a pathway to operations. Test beds are places where new science and technology are evaluated in a setting that mimics NWS operations, thus, facilitating later transfer to operations. Test beds would be regional in scope, focusing on weather hazards and user communities within its region. The test beds would utilize and expand on existing technologies and would investigate optimum methods for combining nowcasting techniques. Universities, government entities, and the private sector are all expected to play strong roles. The test beds would include established and new end users in their activities, would serve as training conduits for both forecasters and users, and would support undergraduate and graduate students. Within the test bed, a rich nowcast database would be developed to support a variety of activities that range from fundamental convective-scale research to verification and user needs assessment. A more thorough discussion is given in the "Test beds: A method for evaluating and improving mesoscale observing networks" section.

MESOSCALE OBSERVATIONS FOR DATA ASSIMILATION AND MODELING.

Introduction. A second important goal of an enhanced mesoscale observing capability (together with nowcasting considerations) is to improve numerical model forecasts of mesoscale weather.[2] Important components of this goal are the a) assessment of needed new measurements, b) development of mesoscale data assimilation systems for optimal use of the observations, c) improvements in model resolution and physics, and d) implementation of targeted observing strategies. All of the components need to be enhanced in concert because all three primary sources of model uncertainty—observation, model, and predictability error—need to be reduced.

A large number of recent studies have clearly demonstrated that mesoscale observations, combined with high-resolution data assimilation and model initialization, can improve short-range forecasts of winds and precipitation. Examples of such studies include Zou and Kuo (1996) and Zupanski and Mesinger (1995), using rainfall observations with a four-dimensional variational data assimilation (4DVAR) approach; Ducrocq et al. (2002), using radar reflectivity, satellite cloud information, and observations from high-resolution surface networks; Sun (2004), utilizing volumetric observations of both radar radial velocity and reflectivity; Gao et al. (2004), employing the full-volume, high-resolution level II

---

[2] Modeling and data assimilation work group coleaders: S. Koch and X. Zou.

velocity data from the WSR-88D network; Smith et al. (2000), using GPS-integrated precipitable water data; Benjamin et al. (2004), using wind profiler data; Jang et al. (2003), utilizing the Total Ozone Mapping Spectrometer (TOMS) ozone data; and Chen et al. (2003), with the initialization of finescale gradients of soil moisture using the 4-km hourly National Centers for Environmental Prediction (NCEP) stage IV rainfall analysis and satellite-derived surface solar insolation data. Improvements in short-range numerical forecasting through advanced data assimilation will benefit not just traditional forecast products, such as quantitative precipitation forecasts and severe weather precursors, but also applications for hydrology, aviation, marine and surface transportation, air-quality modeling, chemical emergency response, urban management, agriculture, and other fields.

Although these and other studies have demonstrated the value of mesoscale observations, they usually have been restricted to the study of observations from a certain type of instrument. The important question for the mesoscale data assimilation and numerical weather prediction (NWP) communities is, given a choice of all possible measurements, what is (are) the optimal mix(es) of observations to obtain the maximum benefit? The answer will no doubt be regionally and phenomenon dependent. Regional, multifunctional 3D mesoscale observing networks are needed to provide a basis for answering this question. Modelers should be involved in the decision process by helping to design observing system experiments to determine a) the most important variables to measure, b) the minimum spacing and resolution requirements (network design), c) adaptive and targeted sampling strategies to minimize the costs and maximize the benefits of taking observations, and d) data assimilation techniques that make the most effective use of these new measurements. The first step in this process is to define the observational needs of future mesoscale models.

Observational needs for mesoscale applications. Although not all forecast error comes from incomplete data, it is clear from examining the primary deficiencies of today's models that current observations are not sufficient for most mesoscale applications. Examples of such deficiencies include the prediction of a) flow in complex terrain, b) the detailed structure of fronts and mesoscale convective systems, c) the detailed evolution of the structure of the planetary boundary layer throughout the diurnal cycle, d) cloud distributions and their interaction with radiation, e) the transport of heat, moisture, and momentum in cumulus parameterization schemes, and f) the explicit prediction of convection. To address these problems, the work group felt that the following observations are needed to most effectively enhance the current observing networks:

- three-dimensional mass, wind, and moisture fields with 10-km (200 m) horizontal (vertical) resolution in the lower troposphere and 10–100-km (0.5 km) horizontal (vertical) resolution in the upper troposphere, with a temporal resolution of 1–3 h;
- more accurate precipitation rates with good quality control;
- three-dimensional hydrometeor fields;
- cloud diabatic heating rate profiles;
- other cloud and microphysical measurements (e.g., entrainment rates, drop size distributions) that are needed to validate and/or design new parameterization schemes;
- daily soil moisture and temperature profiles, vegetation type and state, snow cover and depth, and sea surface temperature (SST);
- turbulent flow, fluxes, and stability measured from the earth's surface to 2-km altitude at 15-min intervals;
- PBL height and structure, (for example, characteristics of convective rolls);
- additional measurements in coastal and mountainous regions, as required by local topographic scales;
- tropopause topology with 10-km horizontal resolution;
- ozone, CO_2, water vapor, and cloud distributions for radiative transfer models; and
- aerosols, chemical tracers, and ground measurements of emissivity and surface temperature.

Note that only those fields that are unobserved or insufficiently observed are included on the above list. The resolution requirements are more demanding than those for nowcasting, because one needs at least six to eight measurements across the space and time scales of mesoscale features in order to predict them well. Resolution needs for the prediction of convective storms are more demanding, because 200–300-m horizontal and vertical resolution is needed, with volume scans every 60 s or less. Note also that these measurements are vital to help quantify mesoscale background error covariances, which are needed for data assimilation and for forecast verification. In addition, an important lesson learned from past field experiments is the need to have accurate observations, well distributed in space and time, in order for the data assimilation scheme to retain the information and for validation of the remotely sensed observations.

Existing and future observing systems could provide the desired mesoscale observations listed above. For example, the dual-polarization upgrade of the WSR-88D radars scheduled for operations in 2009 will improve quantitative precipitation estimation and provide estimates of hydrometeor fields. Future phased-array radars, whether they are extensive Next Generation Weather Radar (NEXRAD)-sited ones or mesonetworks of small, inexpensive systems, would provide the rapid scanning of radial velocity and reflectivity, allowing for adequate storm-scale retrievals. Scanning polarimetric X-band radars (Matrosov et al. 2002), which have been recently demonstrated to be effective in precipitation estimation, present an option that could be less costly than new NEXRAD radars. Other ground-based remote sensing systems, such as AERI (Feltz et al. 1998), slant-range GPS (under investigation), or future scanning multichannel radiometers, could provide vertical temperature and/or moisture profiling, which is especially needed in cloudy regions.

To meet the demands of future operational mesoscale NWP models, future geostationary satellite sounders should have an effective horizontal resolution of at least 5 km and a vertical resolution of 0.5 km, should sample at 15-min intervals, should be able to produce measurements of temperature that are accurate to ±1°C with a relative humidity to ±10%, and should do this with acceptable low data latency. The ability to distinguish fog and low clouds is needed, and the GOES imager horizontal resolution should be 2 km for such purposes. Mesoscale measurements of water vapor, aerosols, and ozone will be possible in cloud-free regions with the planned Advanced Baseline Imager channels that are proposed for GOES-R (scheduled for 2012). A geostationary microwave satellite capability over land areas would complement infrared (IR) interferometer techniques. The Geostationary Microwave Sounder (GEMS) system, being considered for GOES-R, would have 15–50-km resolution above ~2 km altitude, be capable of measuring temperature and moisture profiles within clouds, and also be useful for mapping hydrometeor fields. Future hyperspectral IR satellite measurements on GOES-R promise to have 1600 channels, while the current GOES sounders have only 18 channels. The Hyperspectral Environmental Sounder Suite (HES) is planned to have a severe weather/mesoscale (SW/M) mode that will allow targeted observations over a selected area of 1000 km x 1000 km, with 4-km spatial resolution and updating every 4.4 min. Although radio-occultation measurements of virtual temperature (T_v) from low-Earth-orbiting (LEO) satellites have a good (1 km) vertical resolution above the PBL, their horizontal resolution is coarse because of the long horizontal signal path through the atmosphere between the LEO and GPS satellites. The Constellation Observing System for Meteorology Ionosphere Climate (COSMIC) program is scheduled to launch six LEO satellites in 2005, which should provide thousands of T_v soundings globally per day.

Because the vertical resolution of satellite radiometric measurements is physically limited, it is essential to have a mix of space- and surface-based remote sensing and in situ observations. The work group proposed one scenario, which included a combination of a 10–25-km surface network, a 100-km-resolution national tropospheric profiling network, ground- and LEO-based GPS measurements of moisture and temperature, observations from the GOES-R hyperspectral sounder, GEMS, Moderate Resolution Imaging Spectroradiometer (MODIS) at high latitudes, temperature, wind and moisture information from national and regional airline carriers, a national total lightning network, and dual-polarization and phased-array radar networks. These systems would together provide a very useful composite 3D observing network for generating mesoscale analyses at desired spatial and temporal resolutions, with much improved vertical resolution. Options such as this one should be evaluated in a test bed setting.

Targeted observations. Neither analysis errors nor forecast sensitivities are homogeneous in time or space. It may be more cost effective to deploy intermittent, targeted observations at high resolution rather than only enhancing the present operational networks with additional continuous data at a coarser spatial resolution. For example, the prediction of deep convection (socially important, but extremely challenging) may be significantly improved by targeted observations for 6–12 h prior to its expected development, because deep convection usually has a limited areal extent. It may also be more cost effective to sample only the boundary layer with denser coverage and more observing systems than it would be to attempt to similarly enhance observations in the upper troposphere for improving mesoscale analysis and prediction. Targeted observations are also needed over regions where satellites lack the ability to sample (such as cloudy regions for visible imagers and infrared interferometer instruments), or where observations are contaminated by large errors (such as the lower-tropospheric GPS radio-occultation measurements). Two important examples of current operational observation–targeting programs are the joint NOAA–U.S. Air Force (USAF) dropsonde reconnaissance programs for severe winter weather on the U.S. West Coast (see information online at www.aoc.noaa.gov/article_winterstorm.htm) and the hurricanes in the Atlantic and Caribbean (Aberson and Franklin 1999).

Applications of targeted observations are more challenging for the mesoscale than for large-scale data assimilation and prediction, primarily because a) targeted observations must be repeatedly taken over a domain of appreciable size and at multiple levels to avoid being rejected in mesoscale model predictions, and b) targeted observations may take longer to collect than is useful for short-term forecasts. Targeted systems such as unmanned aerial vehicles (UAVs), constant-altitude balloon swarms, and dropsondes from aircraft platforms are often placed over regions where such additional observations are needed. Although the usefulness of these soundings and/or point measurements for targeting has been demonstrated in many field experiments, radar and satellite targeting may be more effective for mesoscale prediction. For example, the GOES rapid-scan strategy could be extended to areas where the greatest forecast sensitivity has been determined. The scanning strategies for the WSR-88D radar could also be altered to include a greater resolution near the surface, and a wider choice of elevation angle scan options and perhaps sector scans. Electronically scanning, phased-array radars are especially amenable to adapting scanning strategies that are appropriate for the phenomena within range. Observing networks should also have the ability to coordinate and collaborate with each other to optimally sample important phenomena.

The effectiveness of existing targeted observational strategies, such as singular vectors, inverse-tangent linear model perturbations, and ensemble Kalman transform methods, is not proven for predicting the regions of maximum sensitivity at the mesoscale. Similarly, applications of the breeding-mode methods for identifying regions of maximum analysis errors and maximum error growth at the mesoscale are still very limited and are relatively untested. Further studies are needed to find the most effective mesoscale targeting strategy(ies). Test beds that employ prototype-observing networks need to be in place to provide real data tests of the proposed strategies.

Data assimilation. Data assimilation is a process through which all available information is used to estimate as accurately as possible the state of the atmosphere at a specified resolution. This available information includes previous forecasts, observations, dynamical and physical constraints, and statistics (covariances), characterizing the errors in the observations and in the short-range forecast (background) fields that provide the first guess for the analysis. The accuracy and utility of an analysis using the existing data assimilation methods are compromised when the observations and/or the background errors are biased and non-Gaussian, or when observational errors and background errors are correlated. None of the major prediction centers—NOAA/NCEP, the European Centre for Medium-Range Weather Forecasts, the European cooperative High-Resolution Limited Area Model (HIRLAM), or Meteo France—use pure Gaussian correlation functions in their operational analysis systems. Instead, they use polynomials, convex linear combinations of Gaussian functions, Bessel function series, or other methods to approximate background error correlations. However, such methods assume homogeneous and isotropic structures, and may not work well at the mesoscale.

In addition, observational errors are often poorly quantified. Surface observations with high spatial and temporal detail are often rejected in data assimilation systems designed for synoptic-scale flows, owing to the lack of reinforcing data above the surface or poor assumptions of the statistical structure. Optimal treatments of lateral boundary conditions are rarely addressed in data assimilation and forecasts. This seriously limits data assimilation methods in making effective use of mesoscale observations.

It is generally believed that static (intermittent) three-dimensional variational data assimilation (3DVAR) schemes may not work as well for mesoscale data assimilation as do dynamic four-dimensional data assimilation schemes. Observation nudging (Bao and Errico 1997) has been suggested as an effective method for mesoscale data assimilation. However, this method cannot easily use indirect observations (e.g., satellite radiances). Some combination of nudging and variational approaches may be helpful for greater generality. Short-range forecasts and nowcasts of severe weather require that strong horizontal gradients be maintained in the analysis and forecast cycle, which is a challenge for 3DVAR methods. Accounting for rapidly varying vertical structure is also poorly handled today.

The two four-dimensional data assimilation approaches that may work well for mesoscale applications are the ensemble Kalman filter (EnKF) and 4DVAR methods. Advantages of EnKF include admission of a flow-dependent (time varying) background error covariance, a nonlinear evolution of the forecast error covariance, and a relatively less involved system development effort. One major challenge for EnKF is to find representative ensemble members that actually describe real background covariance structures. Another challenge is related to the spin-up problem for the prediction of short-lived mesoscale systems. So far, most numerical tests of the EnKF approach have been restricted to idealized simulations. Further demonstrations with real data are needed at the mesoscale.

The 4DVAR seeks an initial condition such that the forecast best fits the observations within an assimilation time window. Observations are fitted at their exact observing times. The NWP model is used as a strong constraint. The 4DVAR analysis at the end of the assimilation window is identical to that of the extremely expensive ensemble Kalman filter method, provided that the model is perfect and that the error covariance is known at the initial time. The 4DVAR technique is computationally expensive because the NWP model and its adjoint model must be integrated forward and backward to permit the computation of a cost function and its gradient with respect to the initial condition at every iteration of a minimization procedure. Incremental and reduced-order 4DVAR approaches offer an opportunity to substantially reduce the computational cost. Options for relaxing the perfect model assumption are needed, and some have been proposed (e.g., Zupanski 1997).

Although data assimilation seeks to incorporate available observations into the model initial conditions, observations are also needed for constructing and examining the role of mesoscale flow-dependent and time-varying background error covariance and for determining forward model errors (e.g., fast radiative transfer model, terrain mismatch). Observation errors include both instrumental errors (e.g., balloon drift, signals in the true atmosphere not resolved by the instrument), and representativeness errors (grid-scale dependent). Data assimilation and model performance validation require that observational error statistics, including bias and covariance structures in both the horizontal and vertical directions, be quantified, and that these quantifications be available on a continuing basis. Background error covariance structures have been estimated for large-scale assimilation, but there is no guarantee that these structures are valid at the mesoscale. Additionally, the question of representativeness of observations must be reexamined at the mesoscale.

TEST BEDS: A METHOD FOR EVALUATING AND IMPROVING MESOSCALE OBSERVING NETWORKS.

Background. Test beds hold significant promise to help objectively improve current observing systems and to advance the integration of research and development results into operational weather services. However, the term "test bed" remains poorly defined, and the specific role of test beds with respect to improving mesoscale observations is also unclear. The purpose of the test beds work group (TBWG)[3] was to explore these issues; develop a consensus definition of a test bed; and identify key elements, outcomes, and roles for the many partners involved in the provision of weather observations and services. Some specific boundaries and goals were defined for the group as follows:

- emphasize 0–24-h forecasts on the mesoscale as a vehicle for evaluating the mix of observing systems,
- define a test bed within the context of improving mesoscale forecasting applications,
- define the primary attributes of an effective test bed, and
- avoid explicitly prioritizing specific, individual test beds with respect to each other.

As NOAA considers the future of its integrated regional, surface, and tropospheric observing systems (information online at www.nws.noaa.gov/ost/STIP2004.pdf), it faces a key question addressed by this workshop—how to optimize the development and deployment of new measurement systems so as to strengthen the mesoscale observation and prediction capabilities over the United States. Test beds can point the way toward filling this need, and, thus, they became a major focus of the workshop.

Test beds defined. The TBWG developed the following consensus definition of a test bed (Fig. 1). The "blank" in the following paragraph represents a type of phenomenon or forecast problem, for example, air quality, hurricane, hydrometeorology, or severe weather:

> A testbed is a working relationship in a quasi-operational framework among measurement specialists,

---

[3] Test beds work group coleaders are M. Ralph and D. Jorgensen.

> forecasters, researchers, the private sector, and government agencies aimed at solving operational and practical regional ____________ problems with a strong connection to the end users. Outcomes from a testbed are more effective observing systems, better use of data in forecasts, improved services, products, and economic/public safety benefits. Testbeds accelerate the translation of R&D findings into better operations, services, and decision-making. A successful testbed requires physical assets as well as substantial commitments and partnerships.

Test beds can serve a variety of the following purposes: the evaluation of new software on meteorological workstations; conduct of a field campaign during a particular season with the involvement of line forecasters; collection, processing, and dissemination of data from a new observing system; or even the evaluation of a new model not quite ready for operations. The work group concentrated on an observation program test bed—one that investigates a 3D mix of mesoscale observations deployed for the purpose of improving mesoscale weather services. Such a test bed is comprehensive; on one end it includes the deployment of observing systems, on the other, it includes the delivery of products based upon those observations to a wide spectrum of users. In the middle are issues of data communications, quality control of the observations, display of the observations on forecaster workstations or their assimilation into prediction models, model improvements occasioned by the better understanding of atmospheric behavior, and effective methods for judging what difference the observations make in the provision of mesoscale weather services.

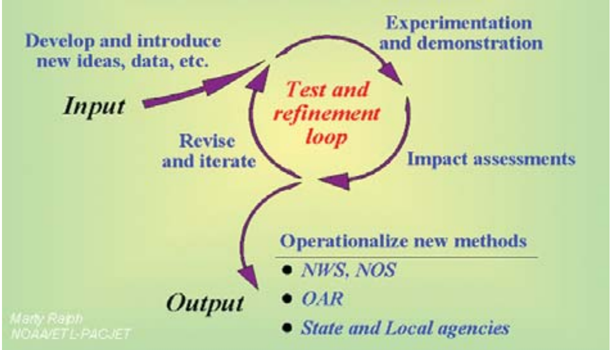

Fig. 1. The test bed as a process. Ideas for improved products and services are demonstrated in a nearly operational setting. If the experimental products or tools stand up to rigorous tests of usefulness, accuracy, reliability, computational efficiency, cost effectiveness, and repeated close scrutiny by users, they can make the transition to operations. Otherwise, user feedback leads to modifications of the products and another round of testing, or to elimination of the candidate tool or method (information available online at www.etl.noaa.gov/programs/2001/pacjet/pacjet_2001_update.pdf).

Many test beds are already in place or being planned, but they all differ from the proposed mesoscale test bed concept in one or more of the following ways: they are narrowly focused on a single application; they do not set out to improve 3D mesoscale observing network design; they do not couple improvements in observations and modeling; and they do not seek to develop partnerships. In the Joint Hurricane Testbed (information online at www.aoml.noaa.gov/hrd/Landsea/jht/), most of the effort is in developing forecast aids based on current datasets and models. The Short-Term Prediction Research and Transition (SPoRT) center (see online at www.ghcc.msfc.nasa.gov/sport/sport_transition.html) is a NASA program that emphasizes the use of mesoscale observations produced by the Earth Science Enterprise in short-term prediction. The Hydrometeorological Testbed (HMT) (information online at www.etl.noaa.gov/programs/2004/hmt/) strives to document gaps in current mesoscale observations and tests solutions using radar, satellite, and other sensors, both for operations and for physical process studies (Ralph et al. 2005). A well-established test bed in the Pacific Northwest (Mass et al. 2003) focuses on regional environmental prediction. As an example of a private sector test bed, Vaisala operates Pacific Lightning Detection Network (PACNET), a test bed in the Pacific Ocean for the collection and processing of lightning observations. The Finnish Meteorological Institute and Vaisala are establishing a short-range, high-latitude mesoscale test bed in Helsinki, Finland, that will assess the benefits of various observing systems and network designs for a range of applications (see information online at www.fmi.fi/testbed). The work group also considered the Oklahoma and west Texas mesoscale networks, as well as a GPS array in Florida. It noted recent field studies in New England and California that focused on mesoscale forecast problems.

The work group examined, as an example, the HMT, a test bed with a strong observational component, research objectives, and a clear connection to operational and user needs. The HMT was developed to improve quantitative precipitation forecasts and resulting streamflow forecasts. It grew out of several field studies of the mesoscale aspects of winter storms striking the U.S. West Coast that brought together forecasters, scientists, and end users. These participants found that mutual interaction was very fruitful, but the episodic nature of traditional scientific field studies strongly limited the long-term benefits. To address this problem, participants developed a strategy to maintain a continuous low-to-moderate level of effort, emphasizing forecaster and user needs. This strategy resulted in the creation of the HMT in 2003 as a NOAA-led effort to address the flood threat on the Russian River. The test bed continued in 2004 and will move to another flood-prone watershed in 2005–07.

The work group concluded that the following five factors must be identified in creating an observation program test bed (examples from the HMT are given for each factor):

- phenomena to be addressed: precipitation/water resources;
- expected outcomes: the increased accuracy of precipitation forecasts and water-resource information through new or improved observations, higher-resolution model grids justified by enhanced observing capability, improved NWS watches and warnings, better physical understanding, and forecaster training;
- special observing networks needed for pilot studies and research: enhanced rain gauge networks, polarimetric radars, soil moisture sensor arrays, wind profiler arrays, targeted mesoscale observations, and research sensors;
- strategies: a regional approach (demonstrations in representative watersheds), water resource data assimilation (multisensor approaches to quantitative precipitation estimation, soil moisture, and snowpack inputs), a high-resolution distributed and ensemble hydrologic modeling comparison of forecast accuracy when specific observation types are included or excluded, physical process studies, identification of products to be evaluated, and generation of evaluation criteria; and
- stakeholders: NOAA (freshwater forecasting), water-resource decision makers (e.g., hydropower, water supply, irrigation), emergency managers (state and local), estuary and ecosystem managers (runoff amounts and water quality), and end users in agriculture and private weather forecasting companies.

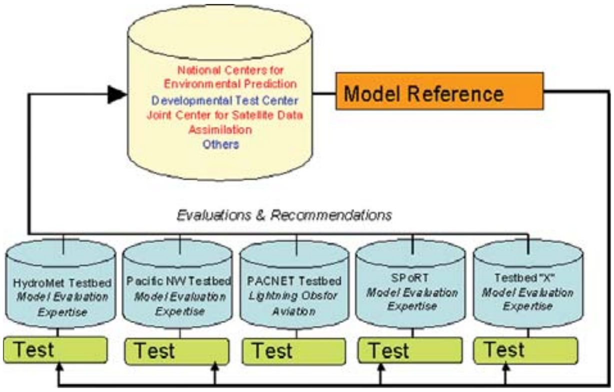

Fig. 2. Proposed relationship between test beds and modeling and assimilation centers. Each test bed obtains a standard reference code—very similar to an operational code—from one of the modeling and data assimilation centers listed at top. Experimental observations are tested within these codes. The codes may have to be modified to accept new sources of observations. Physical parameterizations may need to be modified and tested against the observed behavior. When observations lead to better analyses, forecasts, parameterizations, or other products, the test bed may facilitate their transition into operational codes.

The success of a test bed can be measured in terms of improved products, services, and decisions; improved ways to observe phenomena and understand key physical processes; and, ultimately, better parameterizations of those processes in numerical models. Examples of improved services include better lead time and accuracy of NWS Watches and Warnings, better numerical model guidance, and better use by nonmeteorological decision makers. It is important to recognize that mesoscale observations frequently have multiple uses. Specifically, forecasters use mesoscale observations (e.g., NEXRAD, wind profilers, satellites) to issue warnings, while computer models can assimilate the same data to generate numerical forecasts.

Another role identified for test beds, focusing on observations, is that of improving model parameterizations through physical process studies, which is an important role for the basic research community. Figure 2 suggests that deep phenomenological expertise should be an integral part of the approach, enabling a detailed diagnosis of model physics and the development of new parameterizations.

On the interface between these direct forecaster and numerical model uses lies a new tool—the Interactive Forecast Preparation System (IFPS), an operational method that is used to populate high spatial resolution forecast grids using model data, but modified through human intervention. Test beds that provide high-density observations can play a key role in evaluating and enhancing the performance of this tool.

Observing system development and testing: Balancing research and operational needs. The establishment of test beds that deploy and evaluate new observing systems as part of pilot studies can provide a valuable basis for examining both the operational and research needs of the weather community. This is possible if the observing systems that are specific to the test bed are deployed for a relatively long time (multiple years), with a density that exceeds that of existing networks (regional foci can enable this), and with new sensors. Although observing systems are one basis for advances in both research and operational forecasting, the optimal attributes of observing systems for these two applications can differ substantially (Fig. 3).

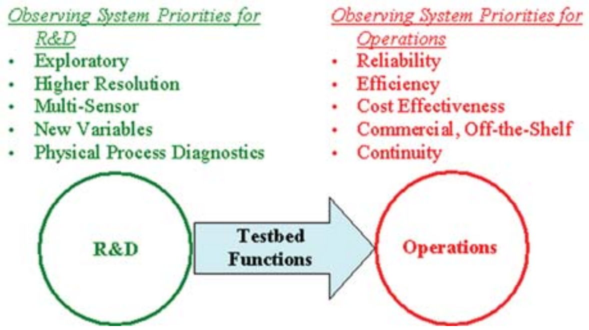

Fig. 3. Test beds and the different observing-system priorities of the research and development and operational communities. Test beds provide the infrastructure for bridging the gap between them. The test bed needs the flexibility to test many new ideas, the expertise to judge which of them are viable, and the infrastructure to harden the sensors and algorithms that will generate new products for operations.

Better understanding of the physical processes that govern weather requires advances in sensors and sensor networks. Trends in the atmospheric sciences include advances in the remote sensing of soil moisture, precipitation, and microphysical conditions, as well as kinematics. In situ development is required for more reliable and lower-cost humidity measurements and for microphysical and aerosol measurements. In addition to the need for better individual sensors for research, the ability to deploy them in large, remote areas simultaneously with many other sensors is critical. In short, basic research and development activities require observing systems that are exploratory, with higher resolutions, multisensor approaches, and capabilities to measure new variables.

From an operational standpoint, the requirements are for low-cost, low-maintenance, and reliable sensors that provide the data critical for operational applications. The availability of these sensors as commercial off-the-shelf (COTS) products helps significantly in acquiring, deploying, maintaining, and replacing the observing networks. In short, operational needs for observing systems emphasize reliability, cost effectiveness, and continuity. The effective use of the data in assimilation systems is also required for numerical prediction applications.

The test bed work group recommended an approach that calls for existing and new sensors that are deployed regionally in a dense array, intended to provide both the unique high-resolution, multisensor data needed for research studies and the opportunity to examine potential oversampling with respect to long-term operational deployments (Fig. 4). For example, during a period of 3 yr, a region might be the focus of study using the test bed approach. In this region, the temporarily dense observing system could be used to test for redundancy between sensors or observing sites. Results from this redundancy analysis could objectively inform decisions about which sites are needed for long-term operational purposes. The redundant sensors would be removed from this region (and could become infrastructure for use in the next region of focus). In the meantime, the test bed sensor array that was put in place for the full 3-yr period could become the focus of one or more traditional episodic intensive

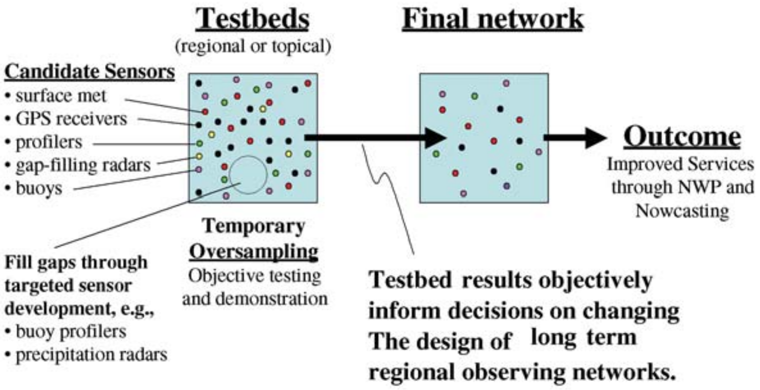

Fig. 4. A conceptual model of a test bed approach is shown that can be used to optimize the evolution of mesoscale observations for long-term use in mesoscale weather services. Temporary oversampling allows researchers to determine the minimum set of observations necessary to sustain improvements in forecasts. Only that set is left in place permanently. [This figure is provided courtesy of Dr. Allen B. White.]

scientific field studies, which would capitalize on the unique array of the test bed sensors and augment them as needed with research aircraft, specialized radars, etc.

Elements of a test bed and infrastructure required. The work group concluded that the most successful test beds are those that engage a broad range of talent and roles, from scientific expertise, to forecasting skill, to user decision making. Much of this talent can be found in operational centers, laboratories, and forecast offices within the federal government; state agencies; universities; and private firms; and collaborative/cooperative efforts can be created within these frameworks. However, it was also recognized that a core effort is required, likely engaging more than one of the key organizations through dedicated staff and facilities (e.g., computing, observing systems), as well as through granting activities. Given its combined forecasting and national research laboratory functions, NOAA is well suited to carry out the core activities in partnership with the other entities mentioned above.

A test bed that is focused on mesoscale observing networks will need a different mix of facilities and staff than a test bed that is focused mostly on numerical modeling or forecast aids. The latter kind of test bed conducts trials and evaluations of new forecast techniques and products, whereas the former concentrates more on testing new observing system combinations for real-time use by forecasters and carries out research on physical processes. Both of these objectives require substantial deployable observing system infrastructure and a combination of engineering, scientific, and forecasting expertise. One of the greatest challenges is to marshal the resources not only for multiyear test bed activities, but also for the long-term implementation of new observing systems. Typically, the cost of test bed activities is low relative to major enhancements in mesoscale observational infrastructure. Moreover, the benefits of the test bed activities will be realized many times over through their impact on the effectiveness of the permanent network, the enhanced forecast capabilities that emerge, and the resulting societal and economic benefits that are realized.

IMPLEMENTATION ASPECTS: USERS, USER NEEDS, AND PARTNERSHIP OPPORTUNITIES FOR THE PUBLIC–PRIVATE–ACADEMIC SECTORS.

Overview. Currently, there are a number of mesoscale networks operating throughout the United States with various levels of accuracy, quality control, resolution, etc. The existing mesoscale networks are of various types and configurations; most are public, some are private, and a few are academic. Some consist only of surface stations, others include only remote sensing systems, while a few include a mix of in situ and remote sensors. There is a compelling need for a more comprehensive mesoscale observing network (or a system of networks) across the United States to support a national or series of regional mesoscale forecasting and nowcasting models, and to assist in more timely forecasts and warnings for a large spectrum of users (see, e.g., Interagency Working Group on Earth Observation 2004). The history of federal support for observing systems has been mixed, and it is timely to consider alternative support mechanisms, including nontraditional approaches.

An important goal of the workshop[4] was to explore the potential for forming viable collaborations among public, private, and academic partners (PPAP) to move mesoscale networks to the next level—a national mesoscale capability based on the needs of the user communities, including those of the forecasting community, the general public, various commercial markets, and researchers. It was recognized that designing optimal mesoscale observing networks and strategies is best accomplished by first implementing mesoscale test beds, as discussed in the preceding section. The implementation work group examined several business models, leaning toward one that consists of a consortium of PPAP to develop, maintain, and support regional mesoscale networks or even a composite national network. The benefits, as well as the associated challenges, of consortia are discussed below.

DEFINITIONS

- Operational: long-term, sustained, continuous, systematic, reliable, and robust, with an institutional commitment
- Raw data: basic observational data with a minimum of processing
- Core products: those produced by the NWS for the benefit of the general public good
- Value-added products: specialized, tailored products for specific markets
- Business model: a strategy that yields a financially and technologically viable mesoscale observing and forecasting capability

---

[4] Work group coleaders are E. W. J. Friday and M. Pirone.

Stakeholders and their roles. The stakeholders in a national mesoscale observation and prediction system include all of the participants in the public, private, and academic sectors of the weather enterprise. The roles and respective strengths of the sectors have been thoroughly discussed in the recent "Fair Weather" report of the National Research Council (2003b). Briefly, the various stakeholder groups include the following:

- The academic community is involved in designing improved data assimilation techniques and forecast models, determining optimal mixes of observations and sampling strategies, developing improved data standards, perhaps providing some instrumentation to the network, using the observational data to further scientific understanding, and developing new-and-improved forecast products. The academic community also makes use of these data in the education of the future generations of weather scientists, policy makers, economists, engineers, and informed citizenry.
- The public sector—local, state, and federal government agencies—traditionally has supported all aspects of the measurements-to-products paradigm, albeit at the synoptic scale. When it comes to a new mesoscale enterprise, government agencies are likely to play a major, if not the dominant, role. They can be expected to support much of the infrastructure needed to collect and disseminate the raw data from government-owned and private measurement systems (and, perhaps, academic systems as well) in the network, to set standards for accepting or certifying new measurement devices and data into the network, and to develop core products for the public to improve understanding and use of weather information.
- Private-sector organizations have an increasing role in providing data from existing private measurement networks, collecting and disseminating data from new mesoscale networks, ensuring data quality, and producing value-added products. In fact, many of the current mesoscale networks are private ventures that make their data and derived products available to private, public, and academic users. Examples of these mesoscale networks include Vaisala's National Lightning Detection Network, roadway weather networks by Surface Systems, Inc. (SSI), and Vaisala, the network of school-based weather stations by AWS, television-owned radar systems and networks developed by Baron Services, Radtec Engineering, Inc., and others, and coastal networks developed by Weatherflow, Inc. Private sector companies are venturing into satellite measurements as well, as in the case of the joint venture between China and the University Corporation for Atmospheric Research that is planning to launch (in December 2005) a constellation of low-Earth-orbiting satellites to measure refractivity. Private weather provider companies (e.g., AccuWeather, WeatherNews, Meteorologix, WDT) are becoming increasingly engaged in developing and providing weather products that were historically viewed as unique to the government sector.
- Policy makers at all levels of government are key stakeholders, making informed judgments about what is in the best interests of the communities they represent.
- Public and private end users are key stakeholders as well; they include fire weather organizations, water management districts, air-quality management boards, emergency responders, and financial entities, among others (see sidebar). Finally, the stakeholder groups include the general public in whose interest basic research, environmental monitoring, and warnings and forecasts are being undertaken for the protection of life and property.

TRADITIONAL STAKEHOLDER GROUPS

- Air quality (federal and state agencies)
- Homeland security
- Agriculture
- Insurance
- Urban management
- Transportation
  - Aviation [airlines, corporate flight departments, fixed base operators (FBOs), pilots, Federal Aviation Administration (FAA)]
  - Surface [trucking, state Departments of Transportation (DOTs)]
  - Marine (shipping, boaters)
  - Railways
- Broadcast media
- Print media
- Energy: power generation, transmission, and distribution
- Power traders
- Weather derivatives traders
- Financial institutions
- Education
- Research laboratories
- Consumers
- Recreation
- Public safety and emergency responders

Why a partnership? The drivers or motivators of effective partnerships must include benefits to each partner. In the weather and climate enterprise, partner-specific returns may include

- return on investment for the private sector,
- the effective accomplishment of the agency mission for the public sector, and
- advancing scientific understanding and the education of future generations of scientists for the academic community, as well as a better-informed citizenry.

Additional drivers include cost sharing (in the form of capital, equipment, intellectual property, human resources, and in-kind services), risk sharing, leveraging of various strengths, and improved access to technical resources and information. The strengths of the partners in the weather enterprise are summarized in Table 1. While recognizing the strengths of the partners, it is equally important to understand their cultural differences. Table 2 illustrates at a very high level the major cultural differences between the public, academic, and private sectors of the weather and climate enterprise.

Models for partnerships in mesoscale networks. Several organizational considerations are necessary in structuring an effective partnership for mesoscale observations. These include legal structures, economic aspects, and operational considerations. The ideal partnership would take the best practices from each sector and blend them to create a unified organization. In this fashion, the innovation and entrepreneurial nature of the private sector might be combined with the stability of a mission-oriented public agency, while leveraging the exploratory motivation of academia.

The infrastructure of the partnership might be centered on the classic “make or buy” decision. For example, should the government take on the entire responsibility for the national mesoscale network by carrying out the entire mission itself or by completely privatizing the effort and “buying” the data it requires for its explicit mission? The latter expedient could vary from buying the data that are needed for the government’s mission with no rights for further dissemination, to buying the complete data rights with no limitations on subsequent use and distribution. In all probability, the optimum configuration would be some hybrid that pieces together a network by bringing in various partners for differing efforts, with the costs and benefits shared equitably among the partners. While the goal is to develop a national mesoscale observing and forecasting capability, that goal may be achieved piecemeal by splicing together multiple regional networks, utilizing different implementation or business models. One example of an existing regional multisector partnership is the Northwest Modeling Consortium (Mass et al. 2003), which funds the development and operation of a mesoscale weather and air-quality prediction system at the University of Washington and Washington State University. The consortium also collects data from 27 separate surface and upper-air networks in the Pacific Northwest, and it has funded the acquisition of a lower-tropospheric UHF wind profiler. The consortium has been in existence more than 10 yr and now includes 15 members: four federal agencies, four state agencies, two local agencies, two universities, and three private companies.

Table 1. Strengths of the public, private, and academic sectors.

Academic	Private	Public
• Science	• Innovation	• Public interest
• Intellectual and technical resources	• Value-added products	• Policy justification
• Research risk taking	• Entrepreneurial spirit	• Infrastructure
• Research centers	• Agility	• Stable environment (including research)
• Neutral ground	• Risk taking	• Standards (data, metadata, interface)
• Multidisciplinary expertise	• Efficiencies	
	• Operational capabilities	
	• Market expertise	

Candidate business models. The implementation work group considered four business models. Although others could be devised, these four cover most of the important options that might be incorporated in the final partnership. The discussion of these individual models serves to illuminate several of the many issues in selecting an appropriate model. Finally, a recommendation is made for the attributes of a business model that may best accomplish the goal of creating viable and effective partnerships.

Table 2. Cultural attributes of the public, private, and academic sectors.

Private sector	Public sector	Academic sector
• Sustain enterprise through profitability	• Maximize public good	• Advance scientific understanding
• Respond to customer needs	• Serve customers within policy	• Pursue academic excellence
• Expand market by offering enhancements	• Provide baseline services	• Improve education
• Maximize return on investment	• Efficiently use funding resources	• Maintain technical resources
• Maximize efficiency of operations and service	• Work within imposed regulations	• Work to the academic cycle
• Take risks for profit reward	• Avoid risks; protect public interest	• Take on research risk
• Focus on outcome	• Focus on stable outcome	• Focus on exploratory and applied research
• Protect proprietary interests	• Promote open environments	Both protect proprietary interests and promote open environments, depending on situation
• Access public assets	• Capitalize on private resources	• Access public assets

Model A: The unified model. In the so-called "unified model," a consortium funds, installs, and maintains the observation network; collects and manages the data; performs quality assurance and quality control on observations, communications, archiving, and modeling activities; creates value-added products; and distributes and sells the data and information products. The revenue generated by the consortium is distributed among members according to a participation formula, probably based on the portion of the total effort funded by each member. Product preparation might be based on member capability. NCEP, for example, might run a sophisticated mesoscale model that would generate what are ordinarily considered value-added products that are above the needs of the government in the performance of its core mission. These products would be generated to serve the needs of all of the members of the partnership, and then sold to the users of those products. In this way a member company might contribute to the needed observational capabilities of the consortium and develop a customer base that uses value-added products generated from its own cutting-edge models, while also using the results of the NCEP operational model (perhaps as boundary conditions for its own proprietary finescale model) to satisfy its clients' needs. NCEP would use its model results to provide for the needs of the NWS in the provision of warnings and forecasts for the protection of life and property. And the NWS/NCEP might also provide the results to other governmental organizations to satisfy their needs, for example, to the U.S. Environmental Protection Agency (EPA) for air-quality analyses and forecasts.

This unified model has the strengths of unity. The unified consortium would be simple to operate, with an attendant clarity of purpose. It would depend essentially on the strengths and interests of each member to parcel out the actions and, thereby, benefit the consortium at large. The shared costs and the prospects for equitable returns would encourage private sector participation. The academic community could be readily entrained in using the data and model output to foster its research and educational missions.

Unfortunately, this model has one major weakness: current law and regulations prohibit the government from selling valued-added weather products. The unified model also departs from decades of public–private "rules of engagement" that give the private sector the value-added role and require that taxpayer-funded data be provided to any user at only the cost of delivery of the data and products. Therefore, if this model were to have a chance of success, a major revision to the legal framework would need to be undertaken. Another important consideration in any consortium involving the public sector is that of unfair competition, that is, whether nonconsortium weather entities would be unfairly treated because of the government's participation. This is a key consideration in the United States where the NWS is a public agency, unlike other entities in this country (e.g., the U.S. Postal Service) and abroad (e.g., the Met Office) that are quasi governmental in nature. Finally, it is unclear whether private weather provider and measurement companies would lose more of their competitive strengths in a consortium than they would gain from access to the core competencies of the other consortium members.

MODEL B: THE CONFEDERATION OF INDEPENDENT ENTITIES. In the "confederation model," the consortium consists of members that collect data from their respective measurement networks. These data are then managed by one or more consortium members, but are readily available to all members of the consortium. The government accesses the data (either freely or at a price) and runs data assimilation and prediction models, uses the model output to provide its required forecasts and warnings, and provides the model output to all potential users. Some confederation members use the data to create and sell value-added products. Private network data providers are compensated for their data under contract with the data users—public, private, and academic alike. Common costs for the network and operations are shared among the confederation members.

The model has the strength of sharing data collection costs, permitting each member to accomplish its mission at a lower cost than by doing everything alone. In this model, the private weather provider sector does what it does best—develops value-added products for its clients. The data archival could be the responsibility of the government, taking advantage of the permanence of the data archival mission of the National Climatic Data Center.

At least one weakness in this model also exists at present; there is a potential for government generation of free products that would interfere with the development of the value-added market. Active coordination of plans within this confederation could minimize this issue to a great extent, but it will probably always exist to one degree or another. The confederation model of independent entities could be initiated relatively easily. No new legislation is required. Careful agreements would need to be negotiated, but they are feasible within the present legal framework. The major difference between the unified and confederation models is that the government is a formal member of the consortium in the former, but not the latter model.

MODEL C: THE FREE-DATA MODEL. In this model, consortium participants invest in mesonet deployment and operations. The data are collected by one or more of the consortium members and are made freely available to all users. The government uses the mesoscale network data to run data assimilation and mesoscale models for the generation of required products for the warning and forecast mission. The government provides the data and products to anyone who requests it at the cost of delivery. The private sector generates value-added products and services for its clients.

The strength of this model is the simplicity of implementation. No special agreements need be developed; no change in any policy is required. The major, and fatal, weakness of this model lies in the lack of incentives for commercial companies to provide data and networks, free of charge, to the common, open mesoscale network. Consequently, there is a very small probability for its successful implementation because nonmember entities would have free access to both the measurement and the model data, leaving little incentive for companies to participate in providing the measurement data.

MODEL D: THE STATUS QUO. In considering new organizational structures, one must always measure change against the status quo. The current environment does include some positive and successful networks, such as the National Lightning Detection Network, and the status quo is certainly easy to implement. On the other hand, it has all the disadvantages that were described in the beginning of this section. Additionally, the chances of rapid progress are limited, and there is little incentive for private investment in new or expanded mesoscale networks, except where there are revenue customers—public or private—to sustain the enterprise.

Recommendation. After considering the strengths and weaknesses of these four business models, the work group proposed a partnership arrangement that leans toward a consortium of PPAP to develop, maintain, and support regional mesoscale networks or even a composite national network. The proposed network(s) would consist of a mix of privately owned measurement systems, publicly owned systems, and newly acquired systems supplied by the consortium. The consortium would collect and quality control the data, and would support the real-time dissemination of data and information products (e.g., analyses and forecasts). The public sector would have access to the data for the public good, for example, public safety. The private sector consortium members would use the data to create and sell various value-added products. Academia and nonprofit research centers would have access to the data for educational and research purposes. And it is also possible that some academic institutions might seek to participate as private partners in the consortium.

The role of government. The successful implementation of any mesoscale business model depends, in very large part, on the future role of the NWS in providing mesoscale observations and forecasting services. The NWS policy that was in effect at the time of the workshop was adopted in 1991 (Office of the Federal Register 1991). That policy was based on the NWS's definition of its own role, as well as the role of the private sector, and sought to avoid competition with the private sector in certain defined areas. A new policy on "partnerships in the provision of environmental information" (see information online at http://weather.gov/fairweather/) was issued 1 December 2004. It is based on a process-oriented approach to defining appropriate roles of the sectors. The revised policy recognizes NOAA's responsibility to support the environmental information enterprise as a whole and requires NOAA's consultation with all of the affected parties, and due consideration of the abilities of other sectors, as NOAA makes decisions about its environmental information services (E. R. Johnson 2005, personal communication).

In view of the dominant influence of the NWS, it is imperative that the NWS facilitate the development, testing, and implementation of mesoscale observing and forecasting systems by working actively with the academic and private sectors and other government agencies to develop a common strategy that works to the mutual benefit of the parties—both public and private—and the stakeholder community.

SUMMARY OF RECOMMENDATIONS TOWARD A MESOSCALE OBSERVING VISION. The underlying message from the 120 workshop participants is clear: existing two-dimensional mesoscale measurement networks do not provide observations of the type, frequency, and density that are required to optimize mesoscale predictions and nowcasts. Moreover, it is unlikely that a single application or a single sector of the meteorological community can provide sufficient resources to remedy the problem. To be viable, three-dimensional mesoscale observing networks must serve multiple applications, and the public, private, and academic sectors must all actively participate in their design and implementation, as well as in the creation and delivery, of value-added products. The mesoscale measurement challenge can best be met by an integrated approach that considers all elements of an end-to-end solution—identifying end users and their needs; designing an optimal mix of observations; defining the balance between static and dynamic (targeted or adaptive) sampling strategies; ensuring data standards and data quality, establishing long-term test beds (i.e., evaluation and demonstration programs); and developing effective implementation strategies.[5] The following summary highlights the major themes and recommendations that emerged.

From an applications perspective, and because of resource considerations, 3D mesoscale measurement networks must serve multiple users and multiple applications. The challenge is to determine the most effective mix(es) of observations. Meeting the challenge requires the development of objective methods for designing and testing alternative network configurations and sampling strategies. For example, it may be more cost effective to sample only the boundary layer with denser coverage than to similarly enhance observations in the upper troposphere for improving mesoscale analyses and predictions. It may be more cost effective to deploy intermittent, targeted observations at high resolution than to maintain dense arrays of sensors that report regularly. Regional test beds are needed to provide a basis for answering these and other questions. Test beds that are built around prototype 3D observing networks should be established to provide real data tests of proposed

---

[5] The workshop recommendations that are summarized here are remarkably consistent with the emerging U.S. plan for participation in the Global Earth Observing System of Systems. The November 2004 draft of the U.S. strategic plan for an integrated Earth observation system (Interagency Working Group on Earth Observation 2004) calls for a need for the improved forecasting of hazardous weather; increased coverage and resolution of observations; observations of environmental elements that are not presently observed; improved timeliness, data quality, and long-term continuity of observations; and integrated multipurpose observing systems and networks that allow for the rapid dissemination of weather information.

strategies. Test beds must carefully gauge the value of forecast products that are provided to end users. Both forecasters and modelers—numerical and empirical nowcasters alike—should be involved in improving the observing network by designing and conducting observing system evaluations to determine

- the most important variables to measure,
- the minimum temporal and spatial resolution requirements (network design),
- adaptive and targeted sampling strategies, and
- data assimilation techniques to effectively use these new measurements.

It was widely acknowledged that current observations are not sufficient for mesoscale modeling, forecasting, and nowcasting applications (details provided in the "Mesoscale observations for nowcasting" and "Mesoscale observations for data assimilation and modeling" sections). Multiple recommendations were made for improved observations. The top observational priority for operational nowcasting is to establish a dense national mesoscale network of surface weather stations that measure winds and state variables and provide real-time subhourly reports. Minimum station spacing should be 25 km, with 10-km or better minimum spacing in areas with significant surface discontinuities (e.g., urban areas, coastal regimes, and mountainous terrain); the reporting frequency should be 5 min or less. NOAA should play a leading role and should set standards for data quality. Radar is an invaluable tool for nowcasting applications, yet the current operational systems have not kept pace with technological advancements. The NWS is urged to expedite implementing a dual-polarization capability to the WSR-88D network. NWS is also urged to implement a recent National Research Council (NRC) recommendation that encourages integrating other (private and academic) radars into the WSR-88D network (National Research Council 2000). Along these lines, NOAA is also encouraged to track and support long-term research on large phased-array and X-band polarimetric radars, as well as techniques for improving boundary layer coverage through the use of closely spaced low-power X-band radars. Research is also needed to test the operational utility of radar refractivity measurements for improved nowcasting. Products detailing near-surface water vapor fields should be provided in real time to forecasters and assimilated into models to demonstrate how high-resolution water vapor fields can improve nowcasting. Research studies are needed to understand how total lightning data can improve severe weather warnings and nowcasts. There is a pressing need for a national expansion of the NOAA Profiler Network, with emphasis on boundary layer observations; NWS is urged to assign this a high priority and to expedite implementation. Not only are additional observations and observing systems required, including in situ and remote sensors (both Earth- and satellite-based), there is a pressing need to seamlessly integrate data from all of the disparate observing systems and to extract maximal information products.

A consensus surfaced concerning the need for test beds and their value in designing networks and sampling strategies; evaluating new observing systems; setting data-quality standards; creating products that better meet user needs; and testing the ability of the public, private, and academic sectors to form effective partnerships to enable operational mesoscale networks. A successful test bed should meet the following criteria:

- address the detection, monitoring, and prediction of regional phenomena;
- engage experts in the phenomena of interest;
- define expected products and outcomes, and establish criteria for measuring success;
- provide special observing networks needed for pilot studies and research;
- define the strategies for achieving the expected outcomes; and
- involve stakeholders in the planning, operation, and evaluation of the test beds.

Test beds require a long-term commitment, usually multiple years. With a view toward improving operational weather services, the observing systems deployed within test beds should be reliable, cost-effective, and commercial off-the-shelf products where possible, and should be capable of sustained, continuous operation. Some redundancy in the observational capability of test beds is needed to make informed decisions about which sites are needed for long-term, routine operations.

The implementation of advanced 3D mesoscale measurement networks entails many practical issues, in addition to the technical and scientific ones. A national network or a collection of regional networks will require a significant commitment and a major infusion of new financial resources. The most viable model for developing and supporting operational mesoscale networks leans toward a consortium of public, private, and academic partners. The mesoscale network(s) themselves would include existing publicly and privately owned measurement systems, and new systems supplied by the consortium. The consortium would collect and quality-control the data, and support the real-time dissemination of data and information products (e.g., analyses and forecasts). Consortium members from the public, private, and academic sectors would each have different incentives to use the data—the public sector, for the public good; the private sector, to create and sell value-added products; and academia, for educational and research purposes.

In the old paradigm of synoptic-scale networks, the government took responsibility for all aspects of the observational problem—design, testing, standard setting, quality assurance, implementation, and operation. But with the reduction in scale size that demands more and improved observations, coupled with improved observing systems, sampling strategies, and modeling systems, a partnership approach was seen as having the greatest likelihood of a successful and timely implementation. For mesoscale partnerships to go forward, it is imperative that the government signal its intention and willingness to lead or participate in public–private–academic partnerships that would operate mesoscale observing networks and develop enhanced value-added weather-based products. Establishing one or more end-to-end mesoscale test beds was viewed as a tangible first step that should be aggressively pursued.

ACKNOWLEDGMENTS. The authors wish to acknowledge, with much appreciation, the key contributions from several persons who contributed to the organization of the workshop and the preparation of this report. Ms. Pam Johnson and Ms. Carrie Kerschner, NCAR, were responsible for all logistical and organizational aspects of the workshop. Ms. Carol Rasmussen, NCAR, edited the final report; and Ms. Ana Salazar, Vaisala, Inc., handled formatting of the document. One of the authors (FC) wishes to acknowledge NSF Grants ATM0129892 and ATM0331594 for support during the organization of the workshop and writing of the report.

REFERENCES

Aberson, S. D., and J. L. Franklin, 1999: Impact on hurricane track and intensity forecasts of GPS dropwindsonde observations from the first-season flights of the NOAA Gulfstream-IV jet aircraft. *Bull. Amer. Meteor. Soc.,* **80,** 421–427.

Bao, J.-W., and R. M. Errico, 1997: An adjoint examination of a nudging method for data assimilation. *Mon. Wea. Rev.,* **125,** 1355–1373.

Benjamin, S. L., B. E. Schwartz, E. J. Szoke, and S. E. Koch, 2004: The value of wind profiler data in U.S. weather forecasting. *Bull. Amer. Meteor. Soc.,* **85,** 1871–1886.

Chen, F., K. Manning, D. N. Yates, M. A. LeMone, S. B. Trier, R. Cuenca, and D. Niyogi, 2003: Development of high resolution land data assimilation system and its application to WRF. Preprints, *20th Conf. on Weather Analysis and Forecasting/16th Conf. on Numerical Weather Prediction,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, 22.3.

Dabberdt, W. F., and T. W. Schlatter, 1996: Research opportunities from emerging atmospheric observing and modeling capabilities. *Bull. Amer. Meteor. Soc.,* **77,** 305–323.

——, and Coauthors, 2000: Forecast issues in the urban zone: Report of the 10th Prospectus Development Team of the U.S. Weather Research Program. *Bull. Amer. Meteor. Soc.,* **81,** 2047–2064.

Ducrocq, V., D. Ricard, J.-P. Lafore, and F. Orain, 2002: Storm-scale numerical rainfall prediction for five precipitating events over France: On the importance of the initial humidity field. *Wea. Forecasting,* **17,** 1236–1256.

Emanuel, K., and Coauthors, 1995: Report of the First Prospectus Development Team of the U.S. Weather Research Program to NOAA and the NSFS. *Bull. Amer. Meteor. Soc.,* **76,** 1194–1208.

Feltz, W. F., W. L. Smith, R. O. Knuteson, H. E. Revercomb, H. M. Woolf, and H. B. Howell, 1998: Meteorological applications of temperature and water vapor retrievals from the ground-based Atmospheric Emitted Radiance Interferometer (AERI). *J. Appl. Meteor.,* **37,** 857–875.

Gao, J., M. Xue, K. Brewster, and K. K. Droegemeier, 2004: A three-dimensional variational data assimilation method with recursive filter for single-Doppler radar. *J. Atmos. Oceanic Technol.,* **21,** 457–469.

Interagency Working Group on Earth Observation, cited 2004: Draft strategic plan for the U.S. Integrated Earth Observation System. Committee on Environment and Natural Resources. [Available online at http://iwgeo.ssc.nasa.gov/draftstrategicplan/IEOS_draft_strategic_plan_111004.pdf.]

Jang, K.-I., X. Zou, M. S. F. V. De Pondeca, M. Shapiro, C. Davis, and A. Krueger, 2003: Incorporating TOMS ozone data into the prediction of the Washington January 2000 winter storm. *J. Appl. Meteor.,* **42,** 797–812.

Mass, C. F., and Coauthors, 2003: Regional environmental prediction over the Pacific Northwest. *Bull. Amer. Meteor. Soc.,* **84,** 1353–1366.

Matrosov, S. Y., K. A. Clark, B. E. Martner, and A. Tokay, 2002: X-band polarimetric radar measurements of rainfall. *J. Appl. Meteor.,* **41,** 941–952.

Miller, P. A., and M. F. Barth, 2003: Ingest, integration, quality control, and distribution of observations from state transportation departments using MADIS. Preprints, *21st Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology (IIPS),* Long Beach, CA, Amer. Meteor. Soc., CD-ROM, 10–11.

National Research Council, 2000: *Weather Radar Technology beyond NEXRAD.* Board on Atmospheric Sciences and Climate, National Academy Press, 83 pp

——, 2003a: *Tracking and Predicting the Atmospheric Dispersion of Hazardous Material Releases: Implications for Homeland Security.* Board on Atmospheric Sciences and Climate, National Academy Press, 114 pp.

——, 2003b: *Fair Weather: Effective Partnerships in Weather and Climate Services.* Board on Atmospheric Sciences and Climate, National Academy Press, 238 pp.

Office of the Federal Register, 1991: Notices, *Federal Register,* Vol. 56, No. 13, Docket no. 91045-1009, p. 1984.

Orville, R. E., 1991: Lightning ground flash density in the contiguous United States—1989. *Mon. Wea. Rev.,* **119,** 573–577.

Ralph, F. M., and Coauthors, 2005: Improving short-term (0–48 hour) cool-seasson quantitative precipitation forecasting: Recommendations from a USWRP Workshop. *Bull. Amer. Meteor. Soc.,* in press.

Smith, T. L., S. G. Benjamin, B. E. Schwartz, and S. I. Gutman, 2000: Using GPS-IPW in a 4-D data assimilation system. *Earth Planets Space,* **52,** 921–926.

Sun, J., 2004: Numerical prediction of thunderstorms: Fourteen years later. *Atmospheric Turbulence and Mesoscale Meteorology,* E. Fedorovich, R. Rotunno, and B. Stevens, Eds., Cambridge University Press, 139–164.

Wade, G. S., T. J. Schmit, W. Feltz, J. P. Nelson III, and A. J. Schreiner, 2003: GOES-11 and GOES-8 sounders during the International H2) Project (IHOP)—2002 field experiment. Preprints, *12th Conf. on Satellite Meteorology and Oceanography,* Long Beach, CA, Amer. Meteor. Soc., CD-ROM, Paper P4.8.

Zou, X., and Y.-H. Kuo, 1996: Rainfall assimilation through an optimal control of initial and boundary conditions in a limited-area mesoscale model. *Mon. Wea. Rev.,* **124,** 2859–2882.

Zupanski, D., 1997: A general weak constraint applicable to operational data assimilation systems. *Mon. Wea. Rev.,* **125,** 2274–2292.

——, and F. Mesinger, 1995: Four-dimensional assimilation of precipitation data. *Mon. Wea. Rev.,* **123,** 1112–1126.