REGIONAL ENVIRONMENTAL PREDICTION OVER THE PACIFIC NORTHWEST

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The experiences of the Northwest Modeling Consortium demonstrate the potential of local modeling as an important component of the future numerical environmental prediction system.

An important issue for the weather and environmental prediction communities is the organization of modeling and associated activities. Should environmental prediction be centralized at a few national centers, decentralized at local forecast centers close to the user communities, or some combination of the two? This issue has become particularly timely as rapidly increasing local computer resources, the availability of state-of-the-art models, and increasing access to observational and model data over the Internet make local environmental prediction increasingly viable (Mass and Kuo 1998). Today approximately three-dozen sites in the United States are running mesoscale atmospheric models in real time using a range of modeling systems, including The fifth-generation Pennsylvania State University–National Center for Atmospheric Research (Penn State–NCAR) Mesoscale Model (MM5), the Coupled Ocean–Atmosphere Prediction System (COAMPS), the Advanced Regional Prediction System (ARPS), the Regional Atmospheric Modeling System (RAMS), and the National Centers for Environmental

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DOI: 10.1175/BAMS-84-10-1353
In final form 22 May 2003

Prediction's (NCEP's) Eta Model (see www.mmm.ucar.edu/mm5/mm5forecast/sites.html for a partial listing). In addition, the use of real-time air quality and hydrological models is rapidly increasing.

The regional numerical prediction effort at the Department of Atmospheric Sciences at the University of Washington (UW) was initiated in 1995 as a single-domain forecast system applying MM5 with 27-km grid spacing. In the succeeding years, it has grown into a regional environmental forecast system that includes atmospheric, hydrologic, and air quality real-time prediction down to 4-km horizontal resolution; a wide range of real-time applications; and the collection of many telemetered observational networks in the Pacific Northwest. A significant contributor to the success of the Northwest modeling effort has been the management and funding by the Northwest Modeling Consortium, a collection of federal, state, and local agencies. This paper reviews the scope and approach of the Northwest modeling effort and examines its implications as a national model.

HISTORY OF THE NORTHWEST REGIONAL PREDICTION EFFORT. The Northwest regional prediction effort began in the early 1990s when a group of Northwest air quality and weather prediction agencies identified the lack of upper-air observations over Puget Sound as a major obstacle for the diagnosis and prediction of local weather and air quality. Under the chairmanship of N. Maykut of the Puget Sound Air Pollution Control Agency, a Northwest Upper-Air Committee was formed and proceeded to identify the Radian 915-MHz radar wind profiler as a possible solution. The group then devised a novel funding approach: support in terms of dollars or other assets (land, personnel) by a "consortium" of agencies. The profiler was purchased in 1992 and remains operational to this day under the care of the Seattle National Weather Service (NWS) office. At roughly the same time, M. Albright, a UW staff member and Washington state climatologist, began construction of a regional real-time weather database for research and forecasting by collecting data from several Northwest weather observation networks into one UW computer server. In such a way a relatively dense mesoscale network was built at little cost, while coordination between different networks reduced duplication of effort. The regional observational database (NorthwestNet) has grown into a collection of over two-dozen networks, including nearly a thousand stations over the Northwest.

During the late 1980s and early 1990s the lead author and several of his students began research simulations of weather features of the west coast of North America using the Colorado State RAMS and the MM4/5 mesoscale models. Running with grid spacing down to 5 km, it was found that such mesoscale models could produce highly realistic mesoscale circulations, particularly those driven by orography, if the synoptic forcing was accurate. By 1994, relatively fast single-processor UNIX workstations became available, making it possible to run regional domains at much higher resolution than used at national modeling centers such as NCEP, where the NCEP Eta Model was being applied at 80-km grid spacing. Based on the promising research runs, the Northwest Upper-Air Committee (soon to be renamed the Northwest Modeling Committee) decided to support the evaluation of local numerical weather prediction (NWP). The initial evaluations completed by J. Steenburgh (then a UW postdoc) were so promising that in 1995 real-time prediction using a single 27-km domain of the MM5 (with initialization and boundary conditions from the Eta Model) was begun using a single processor, an Alphaserver 250. The value of the real-time MM5 prediction system became clear during the next year, as it successfully forecast important regional circulations (such as onshore pushes and coastal surges) for which the Eta Model lacked sufficient resolution.

Research runs had determined that realistic simulation of the major mesoscale features of the North-

Table 1. Membership of the Northwest Modeling Consortium.

Regular Members
National Weather Service
University of Washington
Washington State University
USDA Forest Service
Port of Seattle
U.S. Navy
U.S. Environmental Protection Agency
Washington State Department of Ecology
Puget Sound Clean Air Agency
Washington State Department of Natural Resources
Washington State Department of Transportation
Seattle City Light
Associate Members
Oregon Department of Forestry
Corporate Affiliates
Sun Microsystems, Inc.
KAI Software, Inc.

west required a grid spacing less than 15 km. These results, coupled with the clear value of the 27-km runs, inspired a jump to far higher resolution. With funding from a large collection of agencies ("the Consortium," see Table 1) and an exceptional discount offered by Sun Microsystems, the UW purchased a SUN E4000 server with 14 processors during the summer of 1996. Using this powerful system, a new grid configuration was initiated with a large 36-km domain that extends several thousand kilometers over the eastern Pacific and western North America, and a nested 12-km grid over the entire Pacific Northwest. With the acquisition of upgraded processors the following year, an additional 4-km nest was added over western Washington, making the Northwest effort the highest-resolution NWP effort in the United States for a short period. Additional computers have been acquired during the past 3 yr, allowing the expansion of the 12- and 4-km grids, extension of the simulations to 72 h, and the addition of approximately two-dozen ensemble forecasts at 36- and 12-km grids spacing. During the last few years, the Pacific Northwest prediction effort has grown well beyond atmospheric modeling and diagnosis to perform hydrological, air quality, and smoke dispersion modeling, as well as other applications.

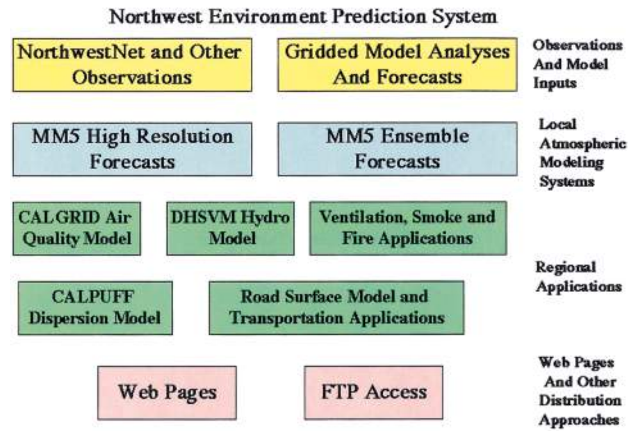

Fig. 1. Schematic of the Northwest Environmental Prediction System.

MAJOR COMPONENTS OF THE NORTHWEST ENVIRONMENTAL PREDICTION SYSTEM.

The Northwest real-time regional prediction system can be divided into four levels (Fig. 1). The top level includes all the observational and model inputs required by the regional models and applications. The second level contains the local atmospheric modeling systems, while the third level encompasses the local environmental modeling systems and applications. The fourth level includes the Web pages and distribution channels through which model output and observations are provided to a diverse user community. A Web portal to all components of the Northwest Environmental Prediction System is found online at www.atmos.washington.edu/pnw_environ/.

Observational and model inputs. All available observations that can be accessed in real-time (or near real-time) are decoded, quality controlled, placed on hard disks for several weeks to several years, and archived on tape. This collection of observations, known as NorthwestNet, is acquired from approximately two-dozen networks (Table 2). A plot of the NorthwestNet surface observations over the state of Washington is shown in Fig. 2. Other groups, including the MesoWest network run by the University of Utah, have taken up this idea of building a network of preexisting observational networks. In fact, NorthwestNet observations are being sent to MesoWest operationally, where they are transferred to the NWS Western Region for dissemination to regional NWS offices for use in the Advanced Weather Information and Prediction System (AWIPS).

In addition to surface observations, the UW effort also gathers all regional upper-air data, including radiosonde soundings, the Seattle 915-MHz profiler temperatures and winds, and the Aircraft Communications Addressing and Reporting System (ACARS) aircraft observations—which are becoming an extraordinary rich source of mesoscale data aloft. Other data sources include all NWS Weather Surveillance Radar-1988 Doppler (WSR-88D) radar data and satellite imagery for the region.

For initialization of the real-time MM5 forecasts, including the ensemble runs, gridded analyses and forecasts are acquired operationally from a number of major prediction centers such as NCEP, the Canadian Meteorological Center, the Australian Bureau of Meteorology, the Taiwan Central Weather Bureau, the Met Office, and the U.S. Navy Fleet Numerical Oceanography Center. Most of these datasets are acquired through file transfer protocol (ftp) servers. For the NCEP products a redundant feed uses the UNIDATA CONDUIT system, in which model grids are distributed over the Internet through a few major sites using the UNIDATA Local Data Manager (LDM) system.

Local atmospheric modeling systems. Penn State–NCAR Mesoscale Model (MM5). Using 38 vertical levels and three nested grids (Fig. 3), the UW real-time system is run twice daily (0000 and 1200 UTC) over all three grids with initialization and boundary conditions from NCEP's Global Forecast System (GFS) model forecasts, which have proven to provide superior synoptic guidance. The MM5 is also run twice a day, for the 36–12-km domains, using the NCEP Eta Model grids, to provide early high-resolution guidance. This type of "cold start," without any local data assimilation or spinup period, was used after tests showed that mesoscale data assimilation using local data assets improved forecasts only during the first few hours. The UW MM5 forecasts are run for 72 h over the 36- and 12-km grids and for 42 h (6–48 h) over the 4-km domain. For the 0000 UTC cycle the MM5 is run with GFS forcing out to 7 days for use in the National Weather Service Interactive Forecast Preparation System (IFPS). Cumulus parameterization (Kain–Fritsch) is only applied over the outer domains. The MM5 output is verified operationally against the NorthwestNet observations and is available online in graphical form or by ftp transfer. More information about the UW high-resolution MM5 runs can be found at its Web site (www.atmos.washington.edu/mm5rt/).

Table 2. NorthwestNet observation networks.

1	U.S. SAO ASOS and AWOS hourly METAR observing network
2	Canadian SAO manual and automated hourly METAR observing network
3	Land 6-hourly synoptic network
4	Ship 6-hourly synoptic network
5	CMAN coastal marine automated network
6	U.S. and Canadian fixed buoy network
7	Drifting buoy network
8	Canadian coastal observing network
9	U.S. coastal observing network
10	U.S. NRCS SNOTEL network
11	USDA Forest Service and Bureau of Land Management RAWS network
12	Northwest Avalanche Center mountain observing network
13	USDA Agrimet network
14	Washington State University public agricultural weather network (PAWS)
15	Hanford–Batelle network
16	Automated Weather Source (AWS) schoolnet
17	Weather Underground personal weather station network
18	University of Washington school network
19	British Columbia RWIS network
20	Washington State DOT RWIS network
21	Washington State Department of Ecology air quality network
22	Washington State DOT ferry marine observing network
23	Puget Sound Energy temperature observing network
24	Seattle City Light network
25	U.S. Geological Survey hydromet network
26	U.S. National Ocean Survey marine network
27	Approximately a half-dozen individual stations

UW mesoscale short-range ensemble forecast system. Operational evaluation of the UW high-resolution forecasts has suggested that poor initialization over the Pacific is a large source of prediction uncertainty. To evaluate such initial condition uncertainty (as well as uncertainty due to model error) and to explore the potential of probabilistic forecasts, MM5 ensemble forecasts were initiated in January 2000 using 5 members and continue today (expanded to 25 members). The UW ensemble system is based on running the 36- and 12-km MM5 domains multiple times using the initializations and boundary conditions from a number of operational modeling systems [e.g., NCEP Eta and AVN models, the U.S. Navy's Operational Global Atmospheric Prediction System (NOGAPS) model, the Canadian Global Environmental Multiscale (GEM) model, the Met Office and Japanese global models, the Australian Global Assimilation Prediction (GASP) model, and the Taiwanese global model]. The central idea is that the variation in the initializations of major modeling systems provides a measure of initialization uncertainty. Additional members of the UW ensemble system are created by varying model physical parameterizations (microphysics, boundary layer schemes, moist physics) and surface properties (variations of sea surface temperature and soil moisture within observational error). Furthermore, UW ensemble work has tested the application of initialization "mirrors," whereby particular initializations are reflected around the ensemble mean (see the Web site provided below for more details). This ensemble work has been facilitated by the purchase of relatively inexpensive Linux clusters through which the ensembles can be efficiently and rapidly computed. Operational for over 2 yr, the initial results of the UW ensemble system are reviewed in Grimit and Mass (2002), and daily forecasts are found online at www.atmos.washington.edu/~emm5rt.ensemble/

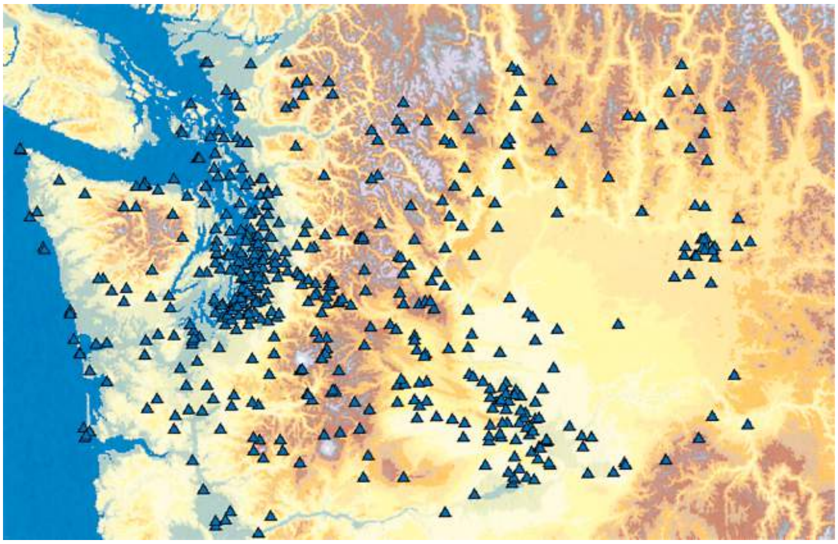

FIG. 2. NorthwestNet surface observation locations over Washington state.

cgi. Figure 4 provides examples of individual ensemble forecasts and derived probability products.

Local environmental modeling systems and applications.

REGIONAL HYDROLOGICAL PREDICTION SYSTEM. Beginning in December 1997, 12- and 4-km output from the MM5 has been used to drive a fully distributed hydrological model [the Distributed Hydrological Soil Vegetation Modeling System (DHSVM)] that was developed by Professor D. Lettenmaier and students at the UW Civil Engineering Department. The coupling of the MM5 and the DHSVM (initially completed by K. Westrick) was so successful that the number of simulated watersheds has been increased from 1 to 26, encompassing most of the river basins in western Washington state (Fig. 5a). Running at 150-m resolution, the real-time streamflow forecasts are made daily out through 60 h, using explicit channel routing that provides streamflow at any point in the river networks. The hydrological predictions are accessible over the Web and distributed to the National Weather Service forecast office in Seattle. For over a year, the UW hydrological prediction system was driven by the ensemble forecasts as well, providing a collection of hydrographs at numerous sites (see Fig. 5b). D. McDonnal of the Seattle NWS office has built an interactive display and analysis system that allows NWS forecasters to view the regional hydrological forecasts and streamflow observations. More information on the UW hydrological effort can be found on the hydrometeorology Web page (http://hydromet.atmos.washington.edu/index.html) or in recent publications (Westrick et al. 2002; Westrick and Mass 2001).

SMOKE AND FIRE GUIDANCE. The suppression of wildfires, as well as the planning and control of prescribed burns in forest and rangeland areas, requires detailed meteorological guidance, particularly over the mountainous Northwest. To provide such information, the United States Department of Agriculture (USDA) Forest Ser-

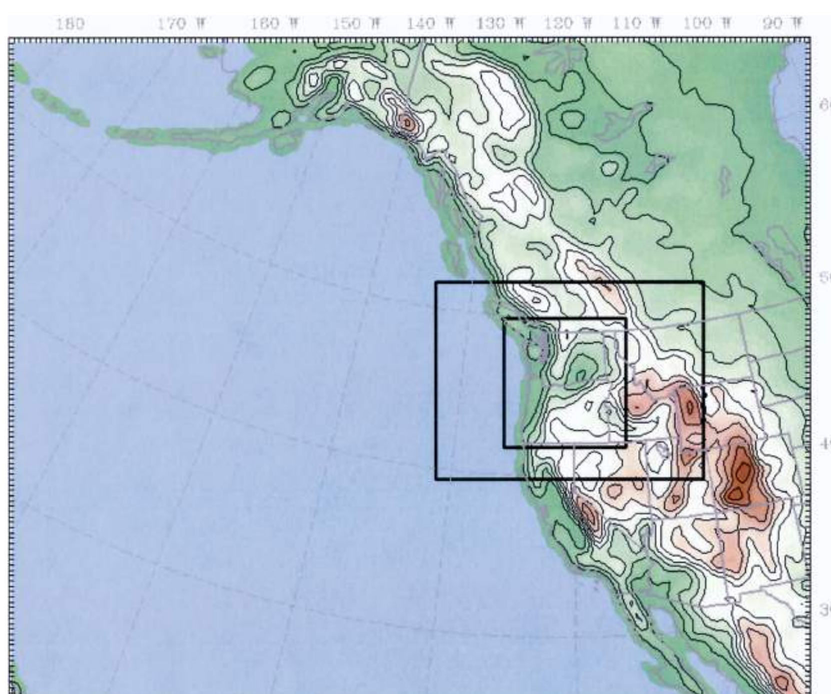

FIG. 3. Model domains for the Northwest real-time MM5 forecasts run at the UW. The grid spacing is 36 km for the outer domain, 12 km for the middle domain, and 4 km for the inner domain. Terrain contours (gray lines) are given every 300 m.

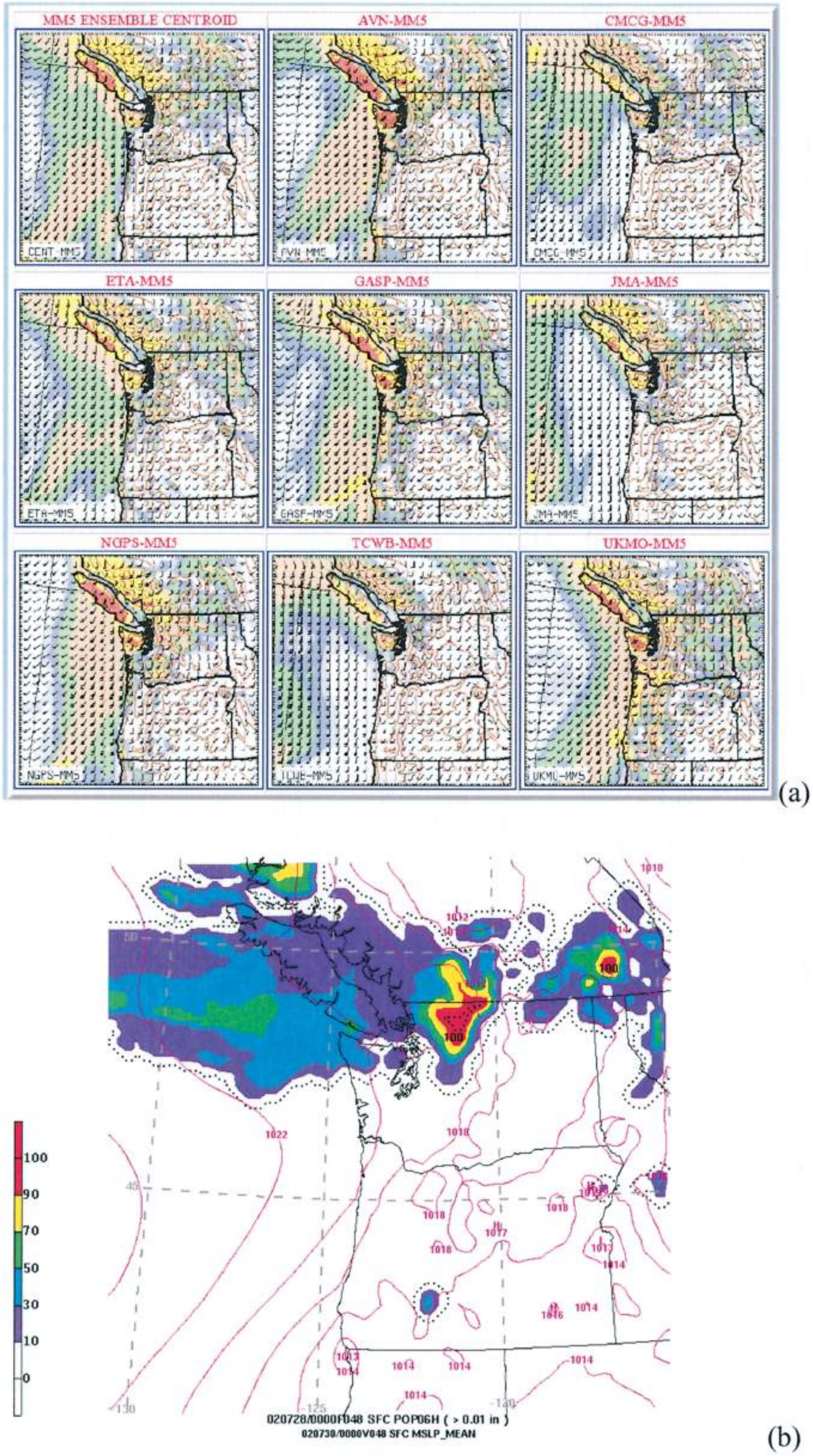

Fig. 4. UW ensemble system products: (a) 3-h precipitation with color shading ranging from heavy (red) to light (blue) and winds (wind barbs) for 48 h into a forecast initialized 0000 UTC 11 Mar 2003 and (b) probability of 6-h precipitation greater than 0.01 inch for a 48-h forecast initialized 28 Jul 2002. On the Web site, both the individual ensemble members and derived products (e.g., ensemble spread, probabilistic forecasts) are provided.

vice is collaborating with the UW and the Consortium to provide a wide range of fire- and smoke-related products driven by MM5 forecasts and regional data assets. Many of these products can be accessed through the Smoke and Fire Web site (www.atmos.washington.edu/gcg/smokeandfire/), which also provides graphical displays of the regional MM5 forecasts, including meteograms and soundings at locations around the Northwest. The site includes guidance products of forecast fire potential (driven by MM5 output), such as the Haines and Fosberg fire indices, and ventilation indices that combine MM5 winds, stability, and boundary layer depths (see Fig. 6a). As part of the Forest Service BlueSky project the regional MM5 grids are interfaced with a Lagrangian "puff" model (CALPUFF) to predict smoke distributions from wild and prescribed fires (Fig. 6b). MM5 graphics and BlueSky smoke predictions are available on EPA's BlueSky-RAINS web site (www.BlueSkyRAINS.org). MM5–CALPUFF is also being applied in an agricultural smoke management system, devised at Washington State University. In this system, MM5–CALPUFF predicts smoke dispersion based on the hypothetical field-burning scenarios. In addition, Oregon Department of Forestry forecasters access MM5 sounding predictions to avoid adverse air quality impacts from prescribed burning.

REGIONAL AIR QUALITY PREDICTIONS. Since the spring of 2001, real-time air quality forecasts have been made over western Washington by using MM5 forecasts to drive an Eulerian photochemical air quality model called the California Photochemical Grid Model (CALGRID), which provides predictions of ozone, nitrogen oxides, and other species of interest. This system has been built by J. Vaughan, B. Lamb, and others at WSU in

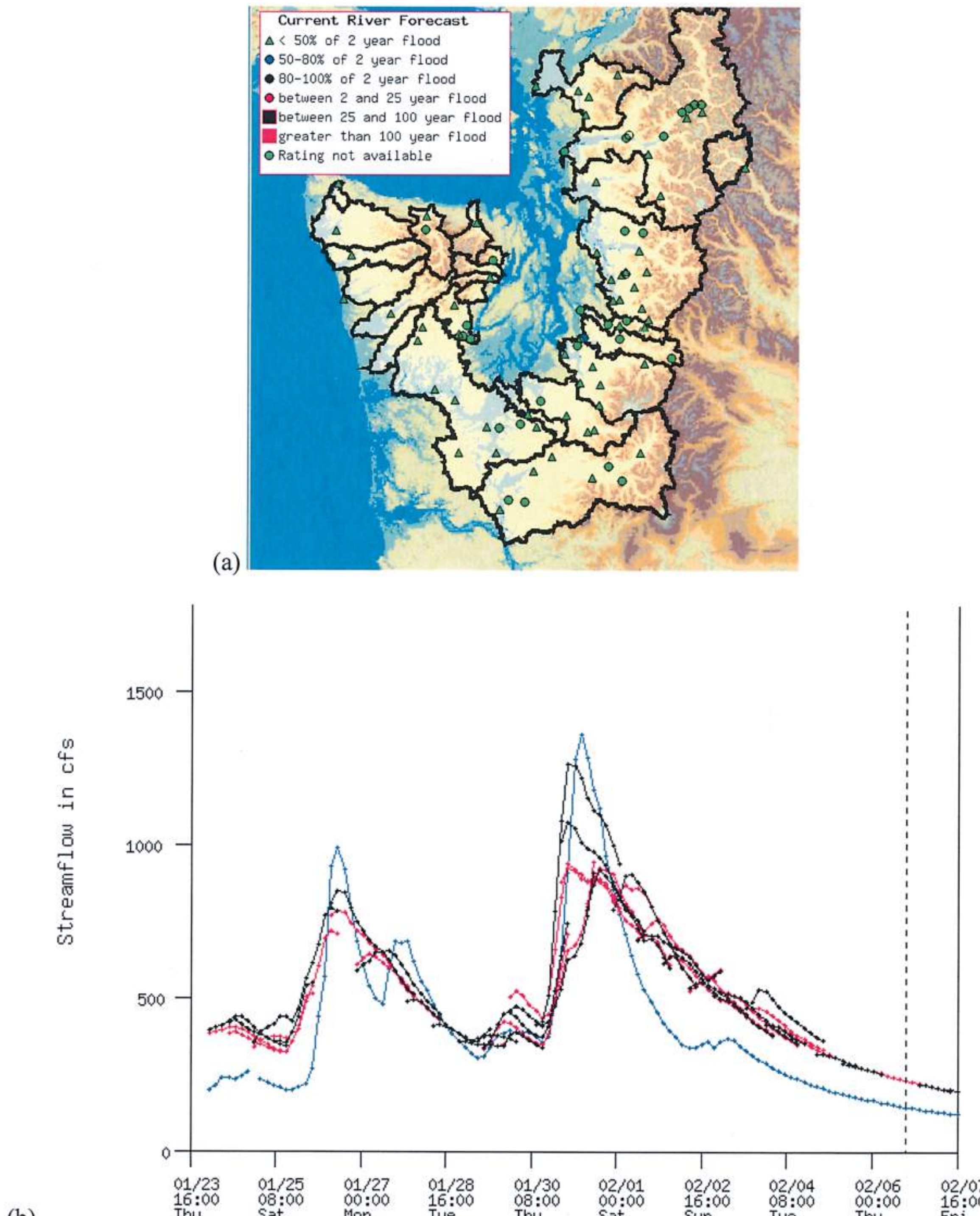

FIG. 5. (a) Watersheds currently modeled operationally in the UW coupled hydrological prediction system. (b) Sample hydrographs showing stream flow on the Raging River near Fall City, WA. The blue represents the observed flow, the red (black) lines are based on forcing from the 12 (4 km) domain. Overlapping hydrographs are from consecutive hydrological forecasts.

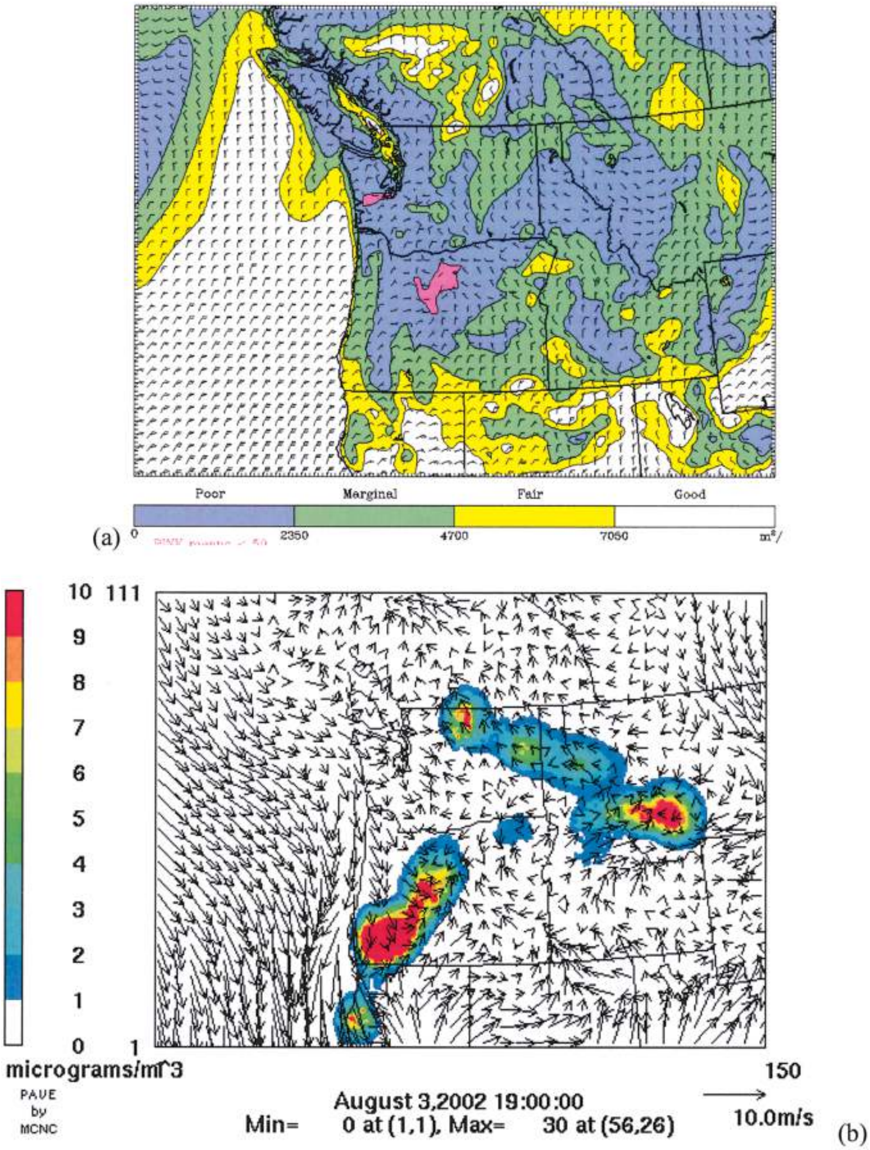

FIG. 6. Smoke and fire products. (a) Ventilation index (18-h forecast) based on MM5 surface winds and low-level stability for 1200 UTC 28 Feb 2002. (b) The 19-h forecast of surface concentrations of particulate matter (less than 2.5 μm in diameter) valid at 1900 UTC 3 Aug 2002, calculated using the CALPUFF Lagrangian dispersion model forced by the 12-km northwest MM5 forecast. The ventilation index is the product of boundary layer wind speed and stability and has units of m^2 s^{-1}.

cooperation with the UW Atmospheric Sciences MM5 group and the U.S. Environmental Protection Agency (EPA) sponsored Air Indicator Report for Public Awareness and Community Tracking (AIRPACT) effort. The coupled MM5–CALGRID system is run once a day at 4-km grid spacing for 24 h using hourly gridded emissions data provided by the Washington State Department of Ecology. Graphical displays of the emissions data and CALGRID forecasts are available at the project Web site (http://airpact.ce.wsu.edu/index2.html). An example of a CALGRID ozone forecast is found in Fig. 7. Further details regarding the Northwest air quality prediction system are found in Vaughan et al. (2003).

ROAD WEATHER INFORMATION SYSTEM. NorthwestNet regional observations and the UW MM5 forecasts are combined to provide guidance for the traveling public and Washington State Department of Transportation (WSDOT) personnel. In addition, the Oregon state land surface model provides forecasts of road surface temperatures for major highways. Through Web portals (www.wsdot.wa.gov/traffic/ or www.wsdot.wa.gov/rWeather/), people can view maps of real-time observations of weather and road conditions as well as forecasts along a particular highway section (Fig. 8). As part of the project, several dozen weather sensors have been placed along state highways and on Washington state ferries that cross the inland waters of the state (see "Ferry Weather" page in Fig. 9).

Web pages and other distribution channels. Both model output and observations are distributed through several channels. A wide range of graphical imagery of the MM5 high-resolution runs, the UW ensemble forecasts, the UW observational data collection, and of the output of the various regional applications and environmental modeling systems are available online (www.atmos.washington.edu/pnw_environ/). Model grids and extracted model soundings are also provided through ftp access for major users, such as the NWS and the USDA Forest Service.

COMPUTATIONAL INFRASTRUCTURE AND MANAGEMENT. With operational integration of a number of models at high resolution and the preparation of thousands of graphical and other products each day, the computational demands for the Northwest modeling effort are correspondingly large. Located at the Atmospheric Sciences Department at the UW Seattle campus, the main computer resources include a 30-processor SUN 6500 server, a 20-processor Athlon (1.2 GHz) Linux cluster, a 32-processor Athlon (1.5 GHz) Linux cluster, over 6 terabytes of Redundant Array of Independent Disks (RAID) disc storage, 2 four-processor servers for integration of the hydrological and air quality models, and four additional machines for pre- and post processing of model data and graphics generation (see Table 3). The excellent scalability of the MM5 on large numbers of processors has been a major factor in allowing high-resolution predictions.

The Northwest MM5 forecasting system has proven to be highly dependable, providing predictions even when NCEP has been down. At the UW such robustness has been made possible by having alternative sources of initialization and boundary con-

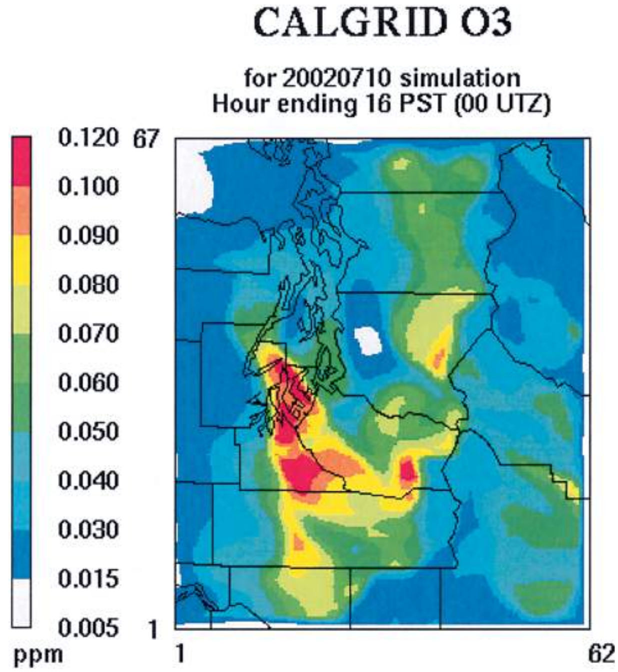

FIG. 7. The 16-h forecast from the coupled MM5–CALGRID system developed by Washington State University. High levels of ozone are forecast southeast and south of Seattle.

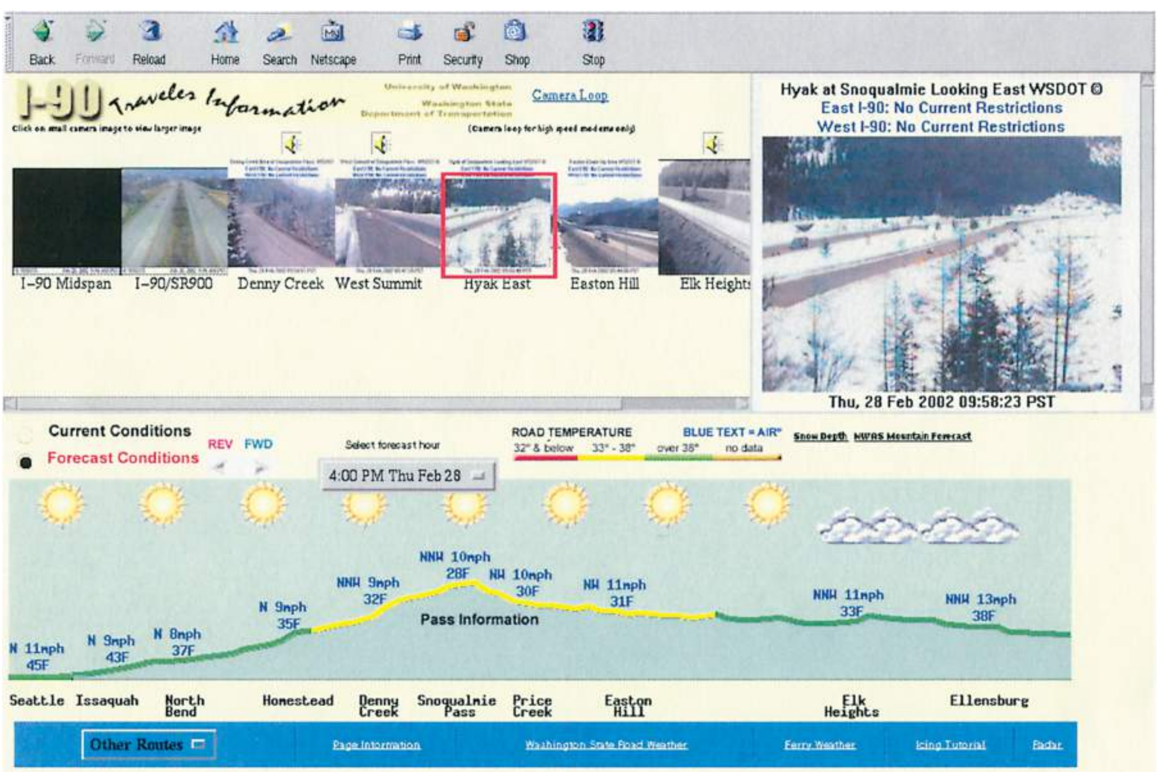

FIG. 8. Interstate 90 (I90) Travel Route Information Web page. (top) Camera imagery across the Cascades, (lower) real-time weather observations and road surface temperatures. In addition, future conditions across the mountains, driven by the UW MM5, can be viewed on this page and clicking on the cross section at any point provides the appropriate NWS forecast.

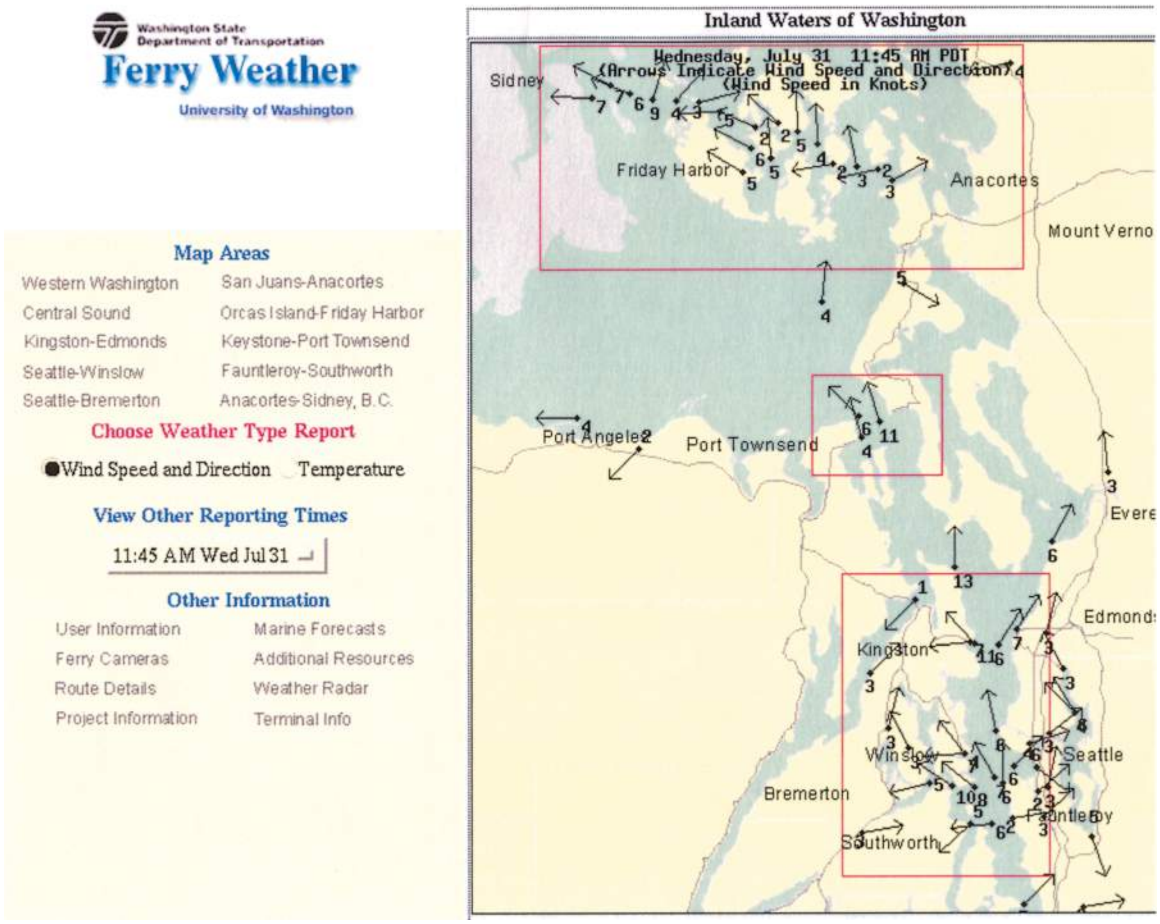

Fig. 9. The Ferry Weather Page that shows weather observations along ferry routes as well as nearby land-based data.

dition grids, multiprocessor machines tolerant of component failures, RAID disk arrays, uninterruptible power supplies that keep models running through power spikes and failures, and complex control scripts that are tolerant of a wide variety of failure modes (e.g., missing grids)—not to mention dedicated monitoring.

Table 3. Current computer resources for the northwest regional modeling effort.

SUN ES-6500 with 30 processors and 4 GB of memory
SUN ES-2500, with four processors.
LINUX Cluster with 20 processors (10 boards with dual 1.2 GHz Athlon processors)
LINUX Cluster with 32 processors (16 boards of dual 1.533 GHz Athlon processors)
Compaq ES-40 server (4 EV-6 500 MHz processors with 3.5 GB of memory)
SUN Ultra 10 for pre- and postprocessing
Approximately 6 terabytes of RAID disk storage, 2 terabytes of non-RAID storage

The Northwest environmental prediction effort is run by the Northwest Modeling Committee and is funded by the Northwest Modeling Consortium (a list of members is provided in Table 1). The committee meets quarterly and makes all major decisions regarding system development and the acquisition of new hardware and resources. Regular e-mail updates are also used to apprise Consortium members of major model changes and for online discussion of important issues between meetings.

THE USER COMMUNITY AND COMMERCIAL "SPINOFFS." The use of Northwest environmental prediction products has grown rapidly over the past five years. The MM5 forecasts are used operationally by local NWS offices, military forecasters, private sector and media meteorologists, and fire-weather, air quality, transportation, and recreational interests—to name only a few. A typical day brings 50,000–150,000 hits (from several thousand unique users) on the MM5 Web page alone. On "interesting" weather days the number of hits can exceed 500,000. Occasionally, local TV weathercasters air UW MM5 graphics, particularly during active weather situations.

Recently, the first commercial spinoff company based on the UW real-time prediction technologies has opened its doors: the 3-Tier Corporation, started by K. Westrick and P. Storck (former UW students and staff members who built the UW hydrological prediction system). This firm offers real-time hydrological, meteorological, and wind energy forecasting services, and runs both the MM5 and DHSVM hydrological models operationally with a large Linux cluster (see their Web site at www.3tiergroup.com/).

REGIONAL RESEARCH. Regional real-time forecast centers not only provide model predictions and derived applications for the local user community, but can also serve as regional research hubs for model evaluation and development. In addition, such efforts can facilitate the creation of new applications for local users based on regional model output and observations. Regional model evaluation and research have the added advantage of being completed by individuals with an intimate knowledge of local weather features and data resources.

Daily real-time forecasts create large datasets that make possible the evaluation of model forecasts far beyond what is possible in case studies, allowing subtle model biases and infrequent failure modes to be determined. Regional real-time prediction systems are powerful test beds for improving mesoscale model dynamics, physics, and data assimilation, advances that are often applicable nationally. Thus, they can be highly productive components of the U.S. Weather Research Program (USWRP) and can be valuable partners to national centers such as NCEP and the Fleet Numerical Meteorological and Oceanography Center (FNMOC).

The Northwest environmental prediction system has facilitated research in a number of areas, as well as spawning major field experiments. A partial list of regional research efforts associated with the Northwest modeling effort includes the following:

- *Effects of increasing resolution:* Using the NorthwestNet Observations, the MM5 forecasts at 36, 12, and 4 km have been evaluated, with the results published in several recent papers (Mass et al 2002; Colle et al. 1999, 2000). The essential finding has been that using traditional objective measures of forecast skill (e.g., mean absolute or rms errors), model errors decrease substantially as grid spacing decreases from 36 to 12 km, with far less improvement as grid spacing is decreased to 4 km. The latter result contrasts with subjective evaluations of mesoscale structures, which suggest considerable reduction in model error as grid spacing decreases below 12 km. One explanation is that small timing and position errors preferentially degrade higher-resolution forecasts (which have tighter structures and more amplitude), even if the structures are more realistic (Mass et al. 2002).
- *Mesoscale short-range ensemble methodology and evaluation:* Although a number of studies have explored the value of ensembles for the central United States under convective conditions (e.g., Stensrud et al. 1999), relatively little evaluation has been given to the value of ensembles over coastal regions of substantial terrain. The UW ensemble research effort has taken on such a study. Furthermore, while most ensemble studies have made use of breeding or singular vector perturbation approaches, the UW work is examining the application of initializations from multiple operational centers. The UW ensemble work has demonstrated a robust relationship between model spread and skill (Grimit and Mass 2002). The UW ensemble research group is working closely with a larger collection of UW investigators from statistics, psychology, and the Applied Physics Laboratory in a Department of Defense (DOD) initiative to develop methods for evaluating uncertainty in mesoscale meteorological model prediction, improving statistical methods for dealing with uncertainty, and understanding how forecasters incorporate uncertainty in their forecasts (www.stat.washington.edu/MURI/).
- *Model microphysical parameterizations:* Long-term verification of surface precipitation from the UW real-time system revealed significant problems with the moist physics schemes in the MM5, particularly at the highest resolutions. A particular problem has been overprediction along the windward slopes of terrain. The lack of simultaneous and extensive observations of both basic-state structures and microphysical parameters—needed to evaluate and improve model moist physics—inspired the planning and initiation of a major two-phase field experiment: the improvement of Microphysical Parameterization through Observational Verification Experiment (IMPROVE). In IMPROVE, aircraft flight level and radar observations—in concert with surface radars, profilers, and other observing systems—provided a comprehensive description of frontal

systems approaching the Washington coast and orographic cloud and precipitation structures over the central Oregon Cascades. IMPROVE datasets are now being used to evaluate and improve microphysical schemes in several mesoscale models. [More information is available online at http://improve.atmos.washington.edu; also see the overview paper Stoelinga et al. (2003)].

- *Boundary layer parameterization*: Multiyear verification of the Northwest MM5 forecasts using the medium-range forecast (MRF) Model planetary boundary layer (PBL) parameterization has indicated substantial model biases, including excessive vertical mixing, stronger than observed low-level winds, and insufficient diurnal temperature range (Mass et al. 2002). Long-term and shorter-term verification of other PBL schemes available for the MM5 suggests similar (and other) problems. In recognition of these deficiencies, a joint project between UW Atmospheric Sciences, the UW Applied Physics Laboratory, and the USDA Forest Service is evaluating and improving PBL schemes for the MM5 and the Weather Research and Forecasting (WRF) models.

LESSONS LEARNED: DOES REGIONAL ENVIRONMENTAL PREDICTION MAKE SENSE? Seven years of real-time meteorological prediction at UW provide some perspective on the viability, value, and potential organization of regional prediction and its relationship to national forecasting centers.

How can regional prediction augment and enhance national prediction efforts? The Northwest modeling experience has demonstrated that a regional effort can optimize the forecasting system for an area and provide additional value to the numerical weather products from national centers. For example, while NCEP was running the Eta Model at 32- and 22-km grid spacing, which is inadequate to model critical Northwest weather features, the Northwest effort was running the MM5 (driven by the Eta Model's initial conditions and boundary conditions) at grid spacings down to 4 km. Equally as important, the NCEP Eta Model's vertical coordinate system does not work well for high-resolution simulations near and over terrain, producing excessive flow blockage and a near absence of realistic mountain waves or downslope wind storms. The sigma-coordinate MM5 was a better choice for the highly mountainous Pacific Northwest. Thus, regional prediction enhanced Eta forecasts over a region for which the Eta's structure was not optimal. With greatly varying physiography and meteorology across the United States, one-size-fits-all numerical weather prediction is not necessarily the best approach.

Local prediction centers, such as UW, can provide full-resolution model output for regional applications and other uses. In contrast, the National Weather Service has had difficulties providing full-resolution model output to even its own offices. For many applications (e.g., local trajectory, dispersion, or air quality models), the current 3-h temporal resolution of NCEP model grids is not adequate and thus local model integration is required.

The creation of an integrated environmental prediction system encompassing atmospheric, air quality, hydrological, and other predictions systems is not only possible but a necessary step for dealing with crucial societal needs, including national security. The UW's effort has shown the potential of coupling a high-resolution mesoscale atmospheric model with a variety of other models and applications. At present, a local prediction system is the only way to create such integration, since high temporal and spatial resolution are required.

The Northwest effort has proven effective in identifying and collecting local weather data for both local and national applications. Regional centers are often aware of data sources not apparent to national centers and can facilitate access to such data through local contacts. In turn, the local centers can contribute regional data to national entities. Furthermore, regional efforts can identify areas where data are needed and work with local organizations to place additional observing assets. Intimate local knowledge allows the identification of problematic observing sites or the determination of where quality control algorithms are rejecting valid data.

As experienced in the Northwest, local prediction centers can enjoy a close relationship with users, garnering quick feedback regarding model strengths and weaknesses. Such interactions encourage rapid improvement in the modeling systems, as well as the tailoring of graphics and output to the needs of the user community.

Local environmental prediction efforts can serve as active centers for model improvement and local research. Such efforts should be viewed as essential components of the USWRP, whereby regional centers contribute improvements to national modeling systems, develop new applications, and evaluate their usefulness to regional users. After rigorous local testing, productive ideas can then feed back to national centers such as NCEP, FNMOC, and the Air Force

Weather Agency (AFWA). Regional centers can serve as repositories of local weather knowledge and act as foci for research on the meteorological phenomena of their area.

Support and management of regional prediction efforts. The Northwest experience has shown that the consortium approach, whereby a collection of local, state, and federal agencies combine resources, is a viable, but time consuming, method to fund such efforts. It has taken several years for a level of trust and ownership to develop among the principals of such a joint enterprise, with patient, empathetic leadership being crucial. A strength of the Northwest consortium experience has been the relative robustness of the funding—although individual agency contributions vary considerably year to year, the aggregate total has been far steadier (typically \$200,000–\$300,000 per annum for operational—nonhardware—support).

The Northwest regional effort grew due to the serendipitous combination of universities with the necessary technical skills (University of Washington and Washington State University) and a forward-looking user community willing to provide needed funding (the Consortium). There is no guarantee of the longevity of the Northwest effort, nor the expectancy that similar cooperative efforts will spring up spontaneously in all regions of the country in which they would prove beneficial. For this reason, national organization and at least partial funding will be necessary to make the vision of a network of regional centers a sustainable reality. One attempt to provide such a national support structure is the USDA Forest Service funded Fire Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS). FCAMMS was created to foster the development of real-time regional modeling and consortia building at research laboratories in Riverside, California; East Lansing, Michigan; Athens, Georgia; Ft. Collins, Colorado; and Missoula, Montana, as well as the Northwest effort (more information available online at www.fs.fed.us/FCAMMS). Regional prediction efforts could also be formed under the auspices of the U.S. Weather Research Program, or built into the National Weather Service (which is already divided into regions).

There should be no sense of tension or competition between regional and national prediction efforts. Both are required to effectively develop forecasting technology and to serve the user community. One vision of the future of environmental prediction encompasses similar regional forecasting centers across the United States, with close ties to national centers. Funding could come from a single federal agency, multiple federal agencies (e.g., NWS, DOD, EPA), or through federal–local partnerships as done in the Northwest consortium. Another approach would be for the National Weather Service to take on the task of creating and maintaining regional prediction centers that would maintain close ties with NCEP. Precedent for such regional prediction centers already exists in the regional climate centers, which are supported by the National Oceanic and Atmospheric Administration (NOAA).

THE FUTURE OF THE NORTHWEST PREDICTION EFFORT. With large numbers of Web hits and the continual demand for more products, the continued need for the forecast and diagnostic products of the Northwest effort seems clear. During the next few years the Northwest regional prediction effort will evolve in a number of ways:

- The new WRF mesoscale model, the planned replacement for both the MM5 and Eta Models, will be evaluated in parallel runs with MM5 during 2003. If verification scores show improved forecast skill, a switch will be made to WRF.
- During 2003 the Northwest MM5 and hydrological (DHSVM) models will be coupled to a real-time Puget Sound predictive system based on the Princeton Ocean Model (POM), in concert with M. Kawase (UW, Oceanography) and the UW Puget Sound Regional Synthesis Model (PRISM) program.
- The Northwest effort will test real-time mesoscale data assimilation. With the increasing availability of ACARS aircraft data during ascents and descents into Northwest airports, greatly increased numbers of surface reports, the availability of additional radar data, and finally improved local data assimilation analysis tools [e.g., three-dimensional variational (3DVAR) methods, the ensemble Kalman filter], the time has come to reevaluate regional data assimilation over the Northwest. In concert with this work, the Northwest system will probably move to a "warm start" with the model being spun up before the nominal start time.
- The 4-km domain will be expanded to include all of Idaho. Ultra-high resolution domains (1.3-km grid spacing) may be added for Puget Sound and the Columbia River Gorge. Local research efforts (e.g., Sharp and Mass 2002) have shown that for some regional features, such as the Columbia River Gorge, 1.3-km grid spacing is required to produce realistic structures.

- The short-range mesoscale ensemble system will be expanded further and a new generation of regional ensemble-based probabilistic guidance will be created. In concert with a multidisciplinary DOD-sponsored research project, we will calibrate, combine, and/or weight ensemble members using Bayesian and other approaches.
- The regional air quality prediction system will be expanded to encompass the Portland, Oregon, urban area and several air toxic compounds will be added. Work is also under way to convert the system from using CALGRID to using the EPA Community Multi-Scale Air Quality (CMAQ) model that will provide additional capabilities for forecasting particulate matter in the region.
- Work will continue on improvements in model physics, including the moist physics and boundary layer schemes.
- Experimentation has begun on grid-based removal of systematic bias. All modeling systems possess systematic bias, which is often removed at observing sites using methods such as model output statistics. With the use of model grids for forecast dissemination and display, it is crucial to remove such biases on the grid itself. After testing a variety of approaches, the Northwest modeling effort will begin such bias removal on an operational basis.

ACKNOWLEDGMENTS. The U.S. Environmental Protection Agency, NWS Western Region, Puget Sound Clean Air Agency, the USDA Forest Service, and the COMET Outreach Program have provided continuous support over the past decade for both personnel and hardware. The UW PRISM program has provided sustained funding for the development of the real-time hydrological prediction system. The Office of Naval Research has supported the verification and evaluation of real-time high-resolution forecasting, and local U.S. Navy groups (e.g., Whidbey Island Naval Air Station) have given us important feedback and support. We acknowledge the cooperation of NCEP, the Fleet Numerical Meteorological and Oceanographic Center, the Australian Bureau of Meteorology, the Canadian Meteorological Center, the Taiwan Central Weather Bureau, and the UK Met Office in providing operational access to their model grids. Extraordinary discounts provided by SUN Microsystems have greatly facilitated the local prediction effort. Finally, the invaluable assistance of department system computer staff (H. Edmon, M. Michelsen, D. Warren) was essential for creating and maintaining the complex hardware/software infrastructure required for such a regional prediction center.

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