Regional Real-Time Numerical Weather Prediction: Current Status and Future Potential

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ABSTRACT

During the past several years, regional numerical prediction efforts have proliferated as local computer power increased, mesoscale modeling systems became easier to use and more readily available, and model analyses and forecasts from national centers became increasingly accessible over the Internet. This paper surveys real-time numerical forecasting efforts around the country, reviews the conclusions of two recent workshops on the subject, evaluates the role of local real-time weather prediction, and suggests future cooperative efforts.

1. Introduction

A major transition in weather prediction is now occurring, one in which real-time numerical weather prediction (NWP) is spreading from a handful of national centers to literally dozens of groups across the country. Such real-time numerical forecasting, completed locally on single or multiprocessor workstations, has become viable recently due to the confluence of three developments.

1) The availability of modestly priced single and multiprocessor workstations capable of making 24–36-h forecasts at moderate to high resolution within 6 h or less. Multiprocessor workstations make “supercomputer” processing capabilities available for $100,000 or less with university or government discounts.

2) The availability of mesoscale models that run efficiently on workstations such as the Pennsylvania State University—National Center for Atmospheric Research (NCAR) model (MM5) and the Colorado State Regional Atmospheric Modeling System (RAMS) model. These models perform well on multiple-processor workstations, with near-linear increases in performance as additional processors are added.

3) Real-time accessibility of analysis and forecast grids from the operational models run at the National Centers for Environmental Prediction (NCEP). Timely access to NCEP grids over the Internet provides the initial and boundary conditions required to run limited area models.

The ability to run mesoscale weather prediction models locally comes at a time when the demand for high-resolution mesoscale meteorological information is growing rapidly. For example, local air quality, hydrology, and trajectory models require high temporal and spatial resolution for their meteorological inputs—data that mesoscale atmospheric models can readily supply. At universities and colleges, high-resolution mesoscale forecasts are needed to train the next generation of students in state-of-the-art mesoscale analysis and forecasting. Further stimulus for local modeling comes from inadequate internet bandwidth, which, although increasing, is still insufficient for distributing high-resolution model output nationally.

Operational synoptic and mesoscale NWP for the entire nation is now taking place at NCEP, with the Eta model being run at both 48- and 29-km horizontal resolution twice daily. On an experimental basis the Eta model has been run once a day on a 10-km grid
for portions of the United States. With the NCEP activities in mind, are there unique insights and applications made possible by regional NWP efforts? What are the potential relationships between local and national forecasting centers? How can regional modeling efforts work together to address difficult issues of mesoscale predictability, data assimilation, and model physics?

This paper will address these and other questions by first describing some of the potential benefits of local mesoscale NWP. Current regional real-time modeling efforts are reviewed and the results of two workshops on this subject are summarized. The paper ends by discussing some important issues and future directions.

2. Why regional real-time numerical weather prediction?

As noted above, real-time mesoscale numerical weather prediction at regional sites is now possible because of improved workstation performance, the availability of suitable mesoscale models, and ready access to gridded analyses and forecasts for initialization and boundary conditions. At the same time, retrospective mesoscale model simulations at high resolution for a number of areas have demonstrated that such models can often provide realistic forecasts of subsynoptic features (e.g., Xue et al. 1996; Colle and Mass 1996). Experimentation with real-time NWP seems a natural outgrowth of these developments; this section will outline some of the potential benefits and problems associated with this new capability for regional mesoscale numerical weather prediction.

a. Potential benefits

1) REGIONAL MODELING EFFORTS CAN PROVIDE GRIDDED OUTPUT AT HIGH TEMPORAL AND SPATIAL RESOLUTION FOR A VARIETY OF LOCAL USERS

Local modeling efforts offer data at full model resolution for research, teaching, and operational applications. For example, local NWP can provide high-resolution output for use in regional air quality and hydrological models or for classroom exercises in mesoscale meteorology. Such regional model runs can easily produce gigabytes of data per day even for a small domain, a data volume that is currently difficult to distribute over the Internet. Limited Internet bandwidth and hardware restrictions at NCEP have restricted the availability of NCEP model output to 3- or 6-h time intervals on grids of degraded resolution.

2) REGIONAL MESOSCALE MODELING GROUPS CAN EXPERIMENT WITH MODEL PHYSICS, RESOLUTION, AND DATA ASSIMILATION TO OPTIMIZE NUMERICAL FORECASTS FOR THEIR AREAS

Varying geographical regions require differing priorities in model development and application. Furthermore, local meteorologists, intimately aware of regional weather features and data resources, are well positioned for verifying and improving regional mesoscale models. Such local modeling efforts, with full-resolution model output at its disposal, can serve as centers for the study of the mesoscale structures and dynamics of their area. Regional models can also act as “testbeds” for the improvement of regional forecasting and serve as local research centers for the U.S. Weather Research Program (Smith et al. 1997).

3) REGIONAL MODELING EFFORTS CAN BE ACTIVE PARTNERS WITH NATIONAL CENTERS

Model and parameterization improvements developed locally can be shared with national centers such as NCEP and the U.S. Navy’s Fleet Numerical Meteorology and Oceanography Center (FNMOC). The existence of regional modeling efforts allows for more extensive experimentation and testing of alternative parameterizations, numerical schemes, and data assimilation approaches than would be possible at national centers alone.

4) REGIONAL MESOSCALE MODELING EFFORTS ENCOURAGE THE INTERACTION BETWEEN MODELERS AND LOCAL USER COMMUNITIES

Potential local users include National Weather Service (NWS) and military forecast offices; regional air quality, transportation, and resource management agencies; private forecasting and consulting firms; local airports; and the media. These local institutions and businesses have a real need for high-resolution model fields that is not being met today by centralized NWP. Interaction with such groups not only clarifies user requirements and provides feedback, but also helps garner local support and resources for regional modeling.

5) REGIONAL MODELING EFFORTS CENTERED AT UNIVERSITIES PROVIDE STUDENTS WITH “HANDS-ON” EXPERIENCE AND DEEPER UNDERSTANDING OF MESOSCALE MODELING AND OF THE METEOROLOGY OF THEIR REGION

Local modeling efforts provide students with direct experience with running and developing sophis-
ticated numerical models and with the diagnosis of the data-rich model output.

6) **Real-time regional NWP provides insights into mesoscale model performance that cannot be derived from traditional retrospective simulations**

For much of the past decade, mesoscale modeling research has been limited mainly to retrospective research simulations of major events. However, there is much about mesoscale model performance—such as long-term biases and subtle problems with model physics—that can only be appraised using a large number of events over long periods of time. Regular real-time simulations offers the opportunity to produce enough mesoscale forecasts for statistical evaluation.

7) **Regional NWP centers can bring together local observational data resources and provide quality control of regional data**

Local NWP efforts are likely to be more adept at finding and obtaining local data through personal interactions than national centers. Such local modelers should also be in a better position to evaluate the sitting, reliability, and error characteristics of regional data networks. These region data can be used for both improved local initialization and verification, as well as being forwarded to national centers.

8) **Real-time high-resolution model output is highly educational for forecasters and researchers alike**

Even if the forecasts are not always correct, with incorrect synoptic-scale guidance generally the most important source of error, daily model simulations display physically reasonable mesoscale structures, many of which have been previously indefinable by limited observational data. Thus, by frequently viewing high-resolution mesoscale predictions, forecasters and researchers can develop mental pictures of complex mesoscale structural evolution for a wide range of synoptic conditions.

b. Potential problems

There are also a number of potential pitfalls associated with the burgeoning collection of local real-time modeling efforts. For example, increasing numbers of small local numerical prediction projects could siphon off personnel and computing resources without producing either better forecasts or new insights into mesoscale meteorology or numerical forecasting. Duplication of effort is also a possibility when a number of real-time forecasting efforts exist within a limited domain. Lack of coordination between local modeling efforts can result in incompatible or different verification approaches, making meaningful performance comparisons between various efforts difficult or impossible.

A number of approaches might ameliorate the potential problems. First, regionalization of local forecasting efforts, so that a critical mass of personnel and resources are available, is one option (Smith et al. 1997). For example, one or two regional universities in concert with local NWS and military forecast offices or state and local air quality agencies might create an effort of sufficient size and resources to support a vigorous local modeling program. Such regional centers would also reduce local duplication of effort. National coordination and occasional meetings might encourage the improvement and standardization for forecast verification. Most local NWP efforts are either not verifying their forecasts or using traditional approaches such as skill scores and biases. New objective verification techniques that better measure the value added from high-resolution forecasts are needed.

3. Review of regional real-time numerical weather prediction in the United States

Pioneering efforts at local numerical weather prediction have taken place at The Pennsylvania State University (Warner and Seaman 1990), Colorado State University (Cotton et al. 1994), the University of Utah (Horel and Gibson 1994), and at Kennedy Space Center (Manobianco et al. 1996) using the Pennsylvania State University/NCAR mesoscale model (MM4), Colorado State RAMS, the Utah Local Area Model (ULAM), and the Mesoscale Atmospheric Simulation System (MASS) model, respectively. Since the early 1990s the number of groups engaged in real-time mesoscale NWP in the United States has increased rapidly, so that today (October 1997) over a dozen institutions are running a mesoscale model at least once a day. As shown in the summary below (Table 1), although many of these groups are located at universities, regional NWP is also taking place at a number of other institutions including government laboratories and research institutions. The Pennsylvania State University/NCAR mesoscale model, Fifth Generation (MM5) is the most widely used mesoscale
Table 1. Some examples of ongoing real-time government and university mesoscale modeling efforts in the United States as of October 1997.

<table>
<thead>
<tr>
<th>Institution</th>
<th>Modeling system</th>
<th>Resolution (km)</th>
<th>Vertical levels</th>
<th>Domain</th>
<th>Period (h)</th>
<th>Initialization</th>
<th>Cumulus param.</th>
<th>Start times (UTC)</th>
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<tr>
<td><strong>NATIONAL CENTERS</strong></td>
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<tr>
<td>NCEP</td>
<td>Eta (early)</td>
<td>48</td>
<td>38</td>
<td>North America area</td>
<td>48</td>
<td>EDAS</td>
<td>Betts–Miller</td>
<td>0000, 1200</td>
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<td>NCEP</td>
<td>Meso-Eta</td>
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<td>50</td>
<td>North America area</td>
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<td>EDAS</td>
<td>Betts–Miller</td>
<td>0300, 1500</td>
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<tr>
<td>NCEP</td>
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<td>50</td>
<td>Southwestern United States</td>
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<td>EDAS</td>
<td>Betts–Miller</td>
<td>0300</td>
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<tr>
<td>FNMOC</td>
<td>COAMPS</td>
<td>81/27/9</td>
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<td>Western United States/southern Canada</td>
<td>24</td>
<td>NOGAPS</td>
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<td><strong>REGIONAL EFFORTS</strong></td>
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<tr>
<td>University of Washington</td>
<td>MM5</td>
<td>36/12/4</td>
<td>33</td>
<td>Eastern Pacific/Pacific Northwest</td>
<td>48</td>
<td>Cold start–early Eta</td>
<td>Kain–Fritsch</td>
<td>0000, 1200</td>
</tr>
<tr>
<td>The Pennsylvania State University</td>
<td>MM5</td>
<td>36/12</td>
<td>30</td>
<td>Continental United States/eastern United States</td>
<td>36/24</td>
<td>12-h FDDA using reanalyzed Eta grids</td>
<td>Kain–Fritsch</td>
<td>0000</td>
</tr>
<tr>
<td>University of Utah</td>
<td>MM5</td>
<td>27</td>
<td>27</td>
<td>Intermountain region</td>
<td>36</td>
<td>Cold start–Eta</td>
<td>Kain–Fritsch</td>
<td>0000, 1200</td>
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<tr>
<td>National Severe Storms Laboratory</td>
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<td>29</td>
<td></td>
<td>Southcentral United States</td>
<td>36</td>
<td>Cold start–early Eta</td>
<td>Kain–Fritsch</td>
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<td>North Carolina State University</td>
<td>MASS</td>
<td>45/15</td>
<td>25</td>
<td>Eastern United States/Southeastern United States</td>
<td>36</td>
<td>Cold start–early Eta</td>
<td>0000</td>
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<td>NCAR/MMM</td>
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<td>27</td>
<td>Central United States</td>
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<td>Cold start–early Eta</td>
<td>Kain–Fritsch</td>
<td>0000, 1200</td>
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<tr>
<td>University of Wisconsin—Madison</td>
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<td>80/27</td>
<td>26</td>
<td>Continental United States/upper Midwest</td>
<td>48</td>
<td>Cold start–early Eta</td>
<td>Kuo</td>
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<tr>
<td>Naval Postgraduate School</td>
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<td>36/12</td>
<td>30</td>
<td>West Coast/California</td>
<td>24</td>
<td>Cold start–meso Eta</td>
<td>Kain–Fritsch</td>
<td>0000, 1200</td>
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modeling system. Most local modeling efforts apply relatively primitive data assimilation/initialization approaches—typically a cold start (no preforecast data assimilation cycle) using the NCEP Eta Model initial conditions. Figure 1 illustrates the domains used for a number of real-time NWP projects. Although not described in Table 1, only a handful of the real-time mesoscale NWP efforts are verifying and evaluating their forecasts. An excellent source of more information on the various real-time NWP efforts is the listing of local NWP World Wide Web sites maintained by the Mesoscale and Microscale Meteorology Division of the National Center for Atmospheric Research (http://www.mmm.ucar.edu/mm5/mm5forecast/sites.html). To illustrate the range of real-time mesoscale forecasting projects, further details on a sample or regional NWP efforts are provided below.

### a. University of Washington

The regional modeling effort at the University of Washington is sponsored by a consortium of national, state, and regional institutions including local air quality agencies, the National Weather Service, the U.S. Environmental Prediction Agency, the U.S. Forest Service, the Port of Seattle, the U.S. Navy, and COMET (UCAR’s Cooperative Program for Meteorology, Education, and Training). The Pennsylvania State University–NCAR Model (MM5) is run twice a day on a 14-processor SUN ES-4000 server for 48 h on two domains: an outer 36-km domain that covers western North America and much of the northeastern Pacific and a 12-km domain that includes most of Oregon, Washington, and southern British Columbia (Fig. 1a). In addition, an inner domain with 4-km horizontal resolution is run for 24 h. A sample forecast of sea level pressure and near-surface winds is found in Fig. 2. The emphasis of this effort has been the evaluation of high-resolution real-time modeling for a coastal region of complex terrain and to explore new data assimilation–initialization approaches over the data-sparse Pacific. Future plans include mesoscale initialization using regional observations, a nudging-based 12-h preforecast data assimilation period, and the addition of a subgrid-scale orographic drag parameterization.

### b. Colorado State University

At Colorado State University (CSU) the real-time forecasts of the RAMS model were run in real time for several years and have been temporarily discontinued. Using the Forecast Systems Laboratory (FSL)
MAPS analysis for initialization and the NCEP Nested Grid Model (NGM) for time-dependent boundary conditions, the CSU RAMS forecasts were run once a day (0000 UTC initialization) on a dual domain. The outer grid extended over the western three-quarters of the United States and had a horizontal resolution of 100 km, while the nested domain covered mainly Colorado and the southern half of Wyoming with a resolution of 25 km. This effort has put considerable effort into model verification and the evaluation of several precipitation parameterization schemes.

c. University of Oklahoma

The primary objective of the Center for Analysis and Prediction of Storms (CAPS), located at the University of Oklahoma, is to demonstrate the practicality of small-scale numerical weather prediction with an emphasis on deep convection. CAPS has developed its own modeling system, the Advanced Regional Prediction System (ARPS), which has run in real time for several domains. A domain of 9-km horizontal resolution centered on Oklahoma has been run using the NCEP Rapid Update Cycle (RUC) model, modified using local data sources, for initialization and boundary conditions. Nested 3-km runs have evaluated the explicit treatment of convection. In addition, a 60-km domain covering the eastern half of the United States, with an embedded 30-km inner nest centered on Chicago, has been run in near real time.

d. The Pennsylvania State University

At this site, the Pennsylvania State University/NCAR mesoscale model (MM5) is run twice a day for 36 h over an outer (36-km resolution) domain that includes most of the continental United States and a nested 12-km domain that covers a portion of the U.S. east coast (Fig. 1b). Using a four-processor SGI PowerChallenge system, the Penn State effort completes a dynamic initialization on the outer domain, nudging the model toward reanalyzed Eta analyses during a 12-h assimilation period. The 12-km inner grid is started 3 h before the beginning of the forecast period, using interpolated fields from the 36-km domain. An example of a forecast of sea level pressure, wind, and 3-h precipitation for the 12-km domain is presented in Fig. 3.

e. North Carolina State University

At North Carolina State’s Atmospheric Sciences Department, daily forecasts are being made using the MASS hydrostatic mesoscale model developed by Meso, Inc. The model is being run for 36 h on a 45-km coarse grid covering the U.S. east coast and a 15-km one-way interactive nested grid covering the Carolinas and Virginia. This project is a cooperative effort between the NWS forecast office at Raleigh, North Carolina, and North Carolina State University.
to assess mesoscale models’ capability of forecasting winter weather phenomena (such as cold air damming) in the Carolinas.

4. Recent workshops on real-time mesoscale forecasting

Recently, two special workshops were held to discuss local real-time NWP. The first was held in Washington, D.C., at NCEP on 13–14 December 1995, while the second took place at the National Center for Atmospheric Research on 25–26 July 1996. In this section we review the meetings’ agendas and major recommendations.


This meeting was hosted by NCEP and brought together a collection of university and NCEP modelers to discuss the role of local NWP and its relationship with NWS modeling efforts. The current state of local mesoscale forecasting in the United States was first reviewed. At that time it appeared that nearly 25 NWS forecast offices and 22 universities were in some way involved in local NWP. A large number of models was being run including the MASS, MM5, Eta, RAMS, COAMPS, and Lawrence Livermore modeling systems. At the typical site, the model was run twice daily from a cold start using the NCEP Eta model for initialization and boundary conditions. Only minimal attempts at data assimilation or forecast verification had been made at the vast majority of sites. A series of major issues, such as the relationship of university and NCEP modeling efforts and the need for better distribution of model and observational data, was then reviewed. Finally, the workshop ended with agreement on a series of recommendations.

1) Improvements in communications and scheduling are needed to assure timely receipt of full-resolution central guidance at local modeling sites.
2) Increased temporal resolution and spatial subsetting of Meso-Eta output should be used to enhance local modeling.
3) Both NCEP and local modeling efforts should be supported, with additional seed money devoted to regional modeling efforts.
4) The exchange of information and knowledge between local modeling efforts and NCEP should be improved.
5) Mesoscale model verification at local and national levels should be expanded.
6) Efforts should be made to make local observational data available to NCEP.
7) The potential for the distribution of local model data using AWIPS (NWS’s Advanced Weather Information and Prediction System) should be explored.

b. Workshop on Real-Time Mesoscale Modeling in the University Community: 25–26 July 1996

This gathering took place at the NCAR Foothills Laboratory and included over 50 university modelers, representatives of NCEP and several military branches, and other interested parties. The first day of
the meeting began with a review of university-based real-time efforts at The Pennsylvania State University, Colorado State University, University of Oklahoma, University of Utah, University of Wisconsin, and North Carolina State University, as well as mesoscale NWP status and plans at NCEP, FSL, and FNMOC. Then, in a series of presentations, panel/group discussions, and working groups, the future role of university mesoscale NWP was discussed.

The basic recommendations and major findings of the workshop were the following.

1) There are compelling reasons for real-time mesoscale modeling in the university community.
   a. University experimental efforts can explore the impact of improved physics, higher-resolution, and new data assimilation approaches on a regional basis and can pass their findings back to NCEP.
   b. Real-time efforts at universities can help students gain a deeper understanding of mesoscale modeling.
   c. Universities can provide regional foci for mesoscale modeling research, interacting with a wide variety of local agencies, educational institutions, and other groups interested in local weather forecasting.
   d. Real-time efforts provide insights into the ability of mesoscale models for a wide variety of cases, unlike the usual retrospective research simulations that generally deal with major, often damaging events.
   e. Universities can work together on more complex problems, such as mesoscale ensemble forecasting.

2) Improved university access to NCEP model grids is needed.
   a. University real-time modeling efforts are dependent on timely access to high-resolution grids from NCEP models for initialization and boundary conditions. Currently, there are major problems with access to NCEP grids.
   b. Regional modeling efforts require hourly output on the native model grids.
   c. A useful approach would be to sectorize model output, so that regional efforts can access and transfer a small portion of the larger-area NCEP grids.

3) University mesoscale NWP and national centers such as NCEP or FNMOC are highly complementary.
   a. University groups see themselves as real-time experimental mesoscale forecasting efforts and not as operational centers of mesoscale NWP.
   b. University efforts can “push the envelope” of resolution, physics, and data assimilation; advances in modeling techniques can then be passed to national centers.

4) Coordinated national efforts to address key scientific issues related to real-time mesoscale modeling should be encouraged.
   a. Potential areas of national cooperation among universities and national centers include verification approaches, predictability and the use of mesoscale ensembles, improvement of model physics for the 1–15-km resolution domain, regional data assimilation, and development and testing of precipitation parameterizations.
   b. University-based real-time modeling efforts can make major contributions to national programs such as the U.S. Weather Research Program (USWRP) and COMET.

Fig. 3. Model-predicted sea level pressure (mb), lowest model level winds (one full barb represents 10 m s\(^{-1}\)), and 3-h precipitation (mm) at 0300 UTC 29 September from the 12-km inner domain of the Pennsylvania State University real-time MM5 modeling system. This run was initialized at 0000 UTC 29 September 1997 and produced a realistic forecast of the timing and amount of precipitation associated with this significant rain event.
5. Discussion and future directions

With increasing local computer power, the availability of advanced mesoscale models, and timely access to NCEP grids for initial and boundary conditions, regional real-time numerical weather prediction has grown rapidly from being nonexistent a decade ago to now encompassing over a dozen efforts across the country. In section 2, some of the benefits of regional numerical weather prediction were summarized. In addition, possible problems such as duplication of effort and the lack of uniform verification approach were noted.

Virtually all regional NWP efforts are dependent on rapid access to NCEP analyses and forecasts for initialization and boundary conditions. Most local NWP groups acquire the gridded analyses–forecasts through NCEP servers that are accessible over the Internet. Because of disk storage and bandwidth limitations at NCEP, grids have generally been available only at 6-h intervals, which is insufficient for properly defining synoptic- and mesoscale features entering model boundaries. As a result, some regional forecasting groups have used large outer domains, so that the temporally coarse boundary values do not advect to the interior of the domain during the simulations. Some local modeling groups have also had problems accessing NCEP servers and transferring the large amounts of data required. Although access problems seem to have improved, better approaches for distributing the increasing volume of NCEP model guidance are needed. One method that has been tested for the experimental 10-km NCEP Eta forecasts (“nest in the west”) has been to “tile” the model output into subdomains, so that local modelers need only transfer Eta output for the areas of interest. Establishing an alternative NCEP model server at NCAR or using the UNIDATA Local Data Manager Internet data distribution approach to distribute NCEP model grids are additional possibilities, the former being a recommendation of a recent USWRP coordinating committee meeting. Data transfer must also be established in the opposite direction, providing NCEP and other sites with regional model output and local data sources.

A sensitive issue for real-time NWP efforts is the dependability of their forecast products. If such local efforts provide additional skill over national products or are more easily accessible, regional users and sponsors will come to depend on their availability. The problem, of course, is that local efforts generally will not have the resources, either in personnel or funding, to build systems with the dependability of those existing at national centers such as NCEP. Thus, in general, an important distinction needs to be made between real-time NWP as practiced at most university and other experimental sites and operational NWP as practiced at major national centers such as NCEP or FNMOC, where model failures are rare. However, it must be noted that local workstation-based NWP has generally proven to be highly robust and dependable; usually, the most significant source of failure of these efforts has been the absence of NCEP grids, not local hardware or software failures.

Mesoscale predictability and mesoscale ensembles are other issues that could fruitfully be addressed by local NWP groups on a cooperative basis. Currently, the relationship between increased model resolution and improved forecast skill, although suggestive, is not clear. For example, mesoscale models may have considerable skill in revealing the mesoscale implications of particular synoptic-scale flows, but if the synoptic forecasts have significant errors, the value of the detail produced by the mesoscale models may be limited. The usefulness of high-resolution mesoscale forecasts may well vary by region, and thus mesoscale forecasts of varying resolution in different areas should be informative. For example, the work of Colle and Mass (1996), among others, suggests that mesoscale predictability may be enhanced in regions of complex terrain where the interaction between synoptic-scale flow and terrain is relatively deterministic.

It has also been suggested that mesoscale ensembles, in which mesoscale forecasts are run from a range of perturbed initial conditions, might provide a useful statistical complement to mesoscale model guidance (Brooks et al. 1995). Since the resources required to carry out small ensemble experiments of moderate resolution are comparable to a single high-resolution forecast, local ensemble experiments are viable. One approach would use synoptic-scale ensembles to drive mesoscale models to provide information on the range of predicted mesoscale states associated with the spread of initial synoptic conditions. Considering that the results of predictability/ensemble experiments might differ by region and that considerable computer resources are required for such efforts, the cooperative contributions of a number of regional modeling groups would be quite useful for exploring the ensemble approach.

Local real-time NWP efforts can also make significant contributions to regional data assimilation by evaluating a variety of data assimilation approaches.
for each region. Regional modelers are often more aware of and have easier access to local data sources than NCEP. The impact of these additional observations and other data sources, such as WSR-88D radial winds, on local real-time forecasts can be evaluated for each region. The value of mesoscale data assimilation is still uncertain, and its usefulness may vary. For example, in complex terrain, mesoscale initialization may not always be necessary since in such regions many of the mesoscale flow features result from the interaction between the synoptic-scale flow and orography. In contrast, over the Great Plains mesoscale data assimilation and initialization may be essential since details of the initial state might have a significant influence on future mesoscale evolution. Even where mesoscale data assimilation has value, the period of time in which it has a positive impact is uncertain and may vary regionally.

The rapid growth of local mesoscale NWP raises several questions regarding the future of numerical weather forecasting and the relative roles of central and local integration of numerical prediction models. Should national centers such as NCEP be mainly responsible for global and national numerical forecasts, while the highest-resolution forecasts are made at regional centers or at local sites where highly detailed mesoscale forecasts are needed? The successful use of modestly priced multiprocessor workstations for real-time numerical weather prediction has considerable implications for operations even at national centers. Such centers, which now depend on expensive supercomputers, could turn to the less expensive multiprocessor workstations as a way to increase computer resources at significantly lower costs. Thus, instead of waiting several years for the next generation supercomputer to become available, the flexibility to use multiprocessor workstations could allow more experimentation and earlier initiation of improvements in resolution or physics.

The next few years should see rapid growth in the use of local, real-time NWP for regional applications and private modeling ventures. For example, regional air quality and hydrology models, which demand the highest spatial and temporal resolution, could be run with regional weather forecasting models. Experiments with the integration of regional weather forecasting and air quality models have already begun at several locations around the country. High-resolution mesoscale modeling could also provide short-range predictions for airports, wildfire and forest fire management, toxic fume dispersion, and severe storm forecasting, to name only a few applications. The use of local NWP in the private sector is relatively untapped, with only a handful of private firms offering real-time mesoscale numerical prediction services. One example is Meso, Inc., which has provided high-resolution real-time model forecasts for operations at Cape Kennedy (Manobianco et al. 1996).

In summary, the future expansion of local NWP is a near certainty, being driven by rapidly growing local computing power, increasing model availability, easily accessible gridded analyses–forecasts, and the increasing meteorological data needs of local users in the air quality, resource management, and weather forecasting communities. The meteorological community faces considerable challenges in fostering and applying this new approach to numerical weather prediction. Cooperation among local NWP efforts and between local NWP groups and national modeling centers is essential for encouraging rapid progress in developing mesoscale NWP and in applying it in research and practical applications.

Acknowledgments. This work was supported by the National Science Foundation (Grant ATM-9416866) and COMET (Grant S96-71866). We wish to thank the several participants at the two recent workshops on real-time NWP for stimulating many of the ideas expressed above. In addition, Mark Albright, Harold Brooks, Brian Colle, Jordon Powers, Jimy Dudhia, Jim Steenburgh, and an anonymous reviewer provided many constructive suggestions. Dave Stauffer kindly supplied graphics from the Penn State system. We would also like to thank Bob Gall for initiating and supporting the NCAR workshop on real-time NWP and Jim Breasch for creating the list of real-time NWP sites.

References
