Real-Time Mesoscale Prediction on Workstations

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Abstract

Experience in performing real-time mesoscale numerical prediction forecasts using the Regional Atmospheric Modeling System (RAMS) over Colorado for a winter season on high-performance workstations is summarized. Performance evaluation is done for specific case studies and, statistically, for the entire winter season. RAMS forecasts are also compared with nested grid model forecasts. In addition, RAMS precipitation forecasts with a simple "dump bucket" scheme are compared with explicit, bulk microphysics parameterization schemes. The potential applications and political/social problems of having a readily accessible, real-time mesoscale forecasting capability on low-cost, high-performance workstations is discussed.

1. Introduction

Mesoscale numerical prediction models have been used extensively to support basic research investigating extratropical cyclones (e.g., Keyser and Pecnick 1985; Chang et al. 1989; Kuo and Low-Nam 1990; Orlanski et al. 1991; Kuo et al. 1992; Lapenta and Seaman 1992; Doyle and Warner 1993), mesoscale convective systems (e.g., Chang et al. 1981; Zhang and Fritsch 1988; Tripoli and Cotton 1989; Crook et al. 1990; Schmidt and Cotton 1990; Tao et al. 1991; Cram et al. 1992; Weisman 1992), sea-breeze circulations (e.g., Estoque 1962; Pielke 1974; Mahrer and Pielke 1977; Anthes et al. 1982; Bechtold et al. 1991), and terrain-driven circulations (e.g., Banta 1984; Deardorff et al. 1984; McNider and Pielke 1984; Richard et al. 1987; Segal et al. 1987). Only recently have such models been applied to real-time forecasting guidance (Warner and Seaman 1990; Golding 1992).

In this paper we describe the application of the Regional Atmospheric Modeling System (RAMS), developed at Colorado State University (CSU), to real-time forecasting over the Colorado Rocky Mountains. An important aspect of these real-time forecasts is that they were performed on a super workstation rather than a supercomputer. We thus discuss the potential for performing real-time numerical guidance on workstations and give examples of some of the specialized products that can be produced. We also discuss some of the limitations of such an approach and some of the ramifications of putting specialized numerical forecasts in the hands of the general public.

2. The RAMS Real-Time Forecasting System

a. General model description

The numerical model used for mesoscale prediction is the Regional Atmospheric Modeling System (RAMS) developed at CSU. It is a completely new code that is a merger of a nonhydrostatic cloud model (Tripoli and Cotton 1982) and a hydrostatic mesoscale model (Mahrer and Pielke 1977). A general description of the model can be found in Cotton et al. (1982), Tripoli and Cotton (1982), Tremback et al. (1985), Tripoli (1986), Tremback (1990), and Pielke et al. (1992). The nonhydrostatic version of RAMS was used and the numerical procedures are described in Tripoli and Cotton (1982) and Tripoli (1986). In the vertical, RAMS used a sigma-z terrain-following coordinate and in the horizontal, grids are mapped on the earth’s surface using a polar stereographic projection.

The turbulence scheme used was the Smagorinsky deformation eddy viscosity described by Tripoli and Cotton (1982), where adjustments to the vertical exchange coefficients were made using a Richardson number/moist Brunt–Väisälä frequency enhancement factor. A five-level prognostic soil model was used as described by Tremback and Kessler (1985). The Mahrer and Pielke (1977) radiation scheme is used, which considers the influence of water vapor, ozone, and carbon dioxide on shortwave and longwave radiative transfer. It does not consider radiative influences due to condensate or microphysical species. For this reason, the model does not account for reflected/absorbed shortwave radiation due to clouds nor does
it include additional downward longwave radiation. RAMS does have a radiation option to consider these effects. Its implementation, however, causes the model to run much slower, thereby prohibiting real-time forecasts on the single workstation that was available.

The “wall on top” condition, where w is set to zero at the model top, is used as a top boundary condition. The modified Rayleigh friction scheme described by Cram (1990) and Heckman (1991) was not utilized for this study because of the additional time involved. Future real-time RAMS forecasts, however, will include a damping mechanism at the top since the wall proves to be reflective (Heckman 1991).

There are four levels of moisture complexity in RAMS (see Flatau et al. 1989). They include

i) completely dry,
ii) moisture as a passive tracer,
iii) condensation of all water vapor in excess of saturation, and
iv) activation of the full bulk microphysics scheme.

Because the bulk microphysics option greatly increased model run time, a crude scheme that allowed precipitation was coded. This scheme used option iii and “dumped” to the ground a fraction of the condensate determined by a precipitation efficiency based on cloud-top temperature. The scheme did not include ice phase nucleation, precipitation processes, latent heat release, or evaporation. It only translated the equivalent amount of water in excess of 100% relative humidity to the surface, reduced by a coefficient resembling precipitation efficiency. The difference between the excess of 100% relative humidity and the actual amount translated to the ground was completely removed from the model domain. This scheme provided a crude “dump bucket” method of liquid precipitation.

The Colorado experiment had two interactive nested grids, both active throughout all simulations. The coarse grid covered the western three-fourths of the United States with 36 x 28 points and 100-km grid increment, and the fine grid covered Colorado with 34 x 30 points and 25-km spacing. A plot of these grids is shown in Fig. 1. There were 24 vertical levels with spacing of 300 m near the surface stretching to a constant 1000 m near the model top of 17.5 km.

b. Initialization—MAPS

RAMS was initialized using NOAA’s Forecast System Laboratory’s (FSL) Mesoscale Analysis and Prediction System (MAPS) (Benjamin 1989). MAPS became an operational National Meteorological Center (NMC) product in October 1993 known as the Rapid Update Cycle.

Although MAPS is a primitive equation forecast model, only MAPS analyses were used for this study. A major advantage of the MAPS datasets over the NMC’s products is the resolution, which is of great importance when initializing a mesoscale model. MAPS is a hybrid sigma-isentropic (constant theta) dataset with 60-km horizontal grid spacing, while the NMC datasets available at the time had much coarser resolution. Many important mesoscale features are lost on grids with spacing greater than 60 km. Another advantage of the MAPS dataset is the isentropic coordinate system, which acts as a natural “adaptive” grid system in baroclinic zones.

Perhaps the biggest advantage MAPS has over NMC products is the incorporation of aircraft reports (ACARS), wind profiler data, and surface mesonetwork data along with the standard surface airway observations (SAO) and rawinsondes into the analysis. It is currently not known whether the additional high-resolution data or the analysis technique (an optimal interpolation scheme on isentropic coordinates) has a larger impact on the quality of the MAPS analysis products.

FSL transferred the 0000 and 1200 UTC MAPS analyses each day roughly 3 h after data time. RAMS was initialized with the 0000 UTC dataset, so that overnight runs produced forecasts that were available first thing in the morning (albeit 12 h older than NMC’s products).

c. Time-dependent lateral boundary conditions—NGM

Time-dependent lateral boundary conditions are necessary for a limited area model that is initialized with horizontally inhomogeneous data. A Davies (1983)
relaxation scheme was utilized for this research, in which boundary values of winds, temperature, moisture, and pressure are forced to externally specified values by introducing an extra tendency term to each prognostic equation, which forces the predicted variable toward the available observations or forecasts over a specified time scale.

The time-dependent lateral boundary conditions were provided by the nested grid model (NGM) forecasts disseminated by NMC. A thorough description of the NGM model can be found in Hoke et al. (1989). This was the most restrictive part of the real-time forecasting at CSU. Whenever NMC had computer problems, an unfortunate chain of events resulted. FSL would receive the NGM forecasts late. Then, upon transmitting at the same time each day, only portions of the NGM forecasts received by CSU were complete. This resulted in forecasts of lengths 24, 30, or 36 h instead of 48 h. RAMS, then, would only have forecast boundary conditions out to this time and thus could not run beyond 24, 30, or 36 h. To further illustrate this point, over one-hundred 12-h forecasts were made between mid-November and early April, while eighty 24-h forecasts, fifty 36-h, and only forty 48-h forecasts were made for this period.

The NGM model's smallest grid has a horizontal grid spacing of approximately 84 km at 45°N latitude. Unfortunately, the NGM datasets received were not this spacing but instead had spacing of 1.25° latitude by 2.5° longitude. This spacing translates to nearly 150 km at 45° latitude. Vertically, the NGM model has 16 sigma levels; however, CSU received the degraded version in which 10 pressure levels were provided.

NGM datasets provided forecasts at the following times: 0, 6, 12, 18, 24, 30, 36, and 48 h. The lateral boundary conditions were first updated at 12 h and then at all subsequent NGM forecast times listed. The boundary conditions were linearly interpolated between the time intervals mentioned. This implies that the variables on a zone of points (five in this study) along the domain’s lateral boundaries were assumed to undergo a linear transition from initialization to 12 h, 12 to 18 h, and so on.

Ingesting the NGM datasets into RAMS was accomplished using the isentropic analysis (ISAN) data assimilation package described by Cram (1990), Tremback (1990), and Pielke et al. (1992). This package was used because it is designed for data that are gridded horizontally on a latitude/longitude grid and vertically on pressure levels. This made the output datasets very similar to the MAPS format except that MAPS is on a polar stereographic grid. Once NGM datasets were processed through the ISAN package, they were horizontally and vertically interpolated to the RAMS horizontal and vertical grids.

RAMS was run daily from mid-November 1991 through the first week of April 1992 on a Stardent 3040 workstation at CSU. The model was initialized with the 0000 UTC data and, as often as data allowed, produced forecasts out to 48 h. A 48-h forecast on the Stardent workstation took from 10 to 12 h of wall-clock time depending on machine load. Statistical evaluation of model performance was done both on a case study basis and statistically for the entire season. We illustrate a forecast for one of the major storm events during the period of operation.

3. Prototype real-time forecasting—Colorado experiment

a. Case study: 8–9 March 1992

1) SYNOPTIC OVERVIEW

On 8 March 1992 a synoptic situation favorable for heavy snow along the Colorado Front Range was developing. At the surface, an arctic front was approaching from the north while lee cyclogenesis was occurring in the southeastern portion of Colorado. Moisture was being fed into the storm as a strong fetch of air from the Gulf of Mexico protruded northward and westward through Kansas and into Colorado. Aloft, a split flow regime allowed a cutoff low to move from southern California toward the Four Corners region. By 0000 UTC 9 March the arctic front was pushing through Colorado causing an upslope flow regime to develop along the Front Range and snow followed soon after. The snow began in the northern portions of the state first and intensified throughout the nighttime hours. Embedded convection aided in localized heavy snowfall and many communities reported blizzard conditions and occasional lightning. In fact, prefrontal convection was also present as evidenced by the report of a tornado just to the south of Limon, Colorado, the afternoon of 8 March. By 1200 UTC 9 March, Fort Collins reported 33 cm of snow while residents in the foothills just west of town reported snowfall amounts as large as 71 cm. The surface low at this time had moved into central Kansas and incorporated the arctic front into the system creating a trailing cold front and a more classical extratropical cyclone. The 500-mb cutoff was centered on the Colorado–Kansas border and was beginning to be absorbed in the northern branch of the jet. By 0000 UTC 10 March the whole system had moved into the Great Lakes region, leaving Colorado and the Central Plains in a cold arctic air mass dominated by large-scale subsidence.

2) REAL-TIME RAMS FORECAST

RAMS simulated this developing storm system very well during this 48-h time period. The cyclogen-
esis in southeast Colorado was modeled particularly well. As shown in Fig. 2a, the 24-h predicted mean sea level reduced pressure valid at 0000 UTC 9 March exhibits a 994-mb low in southeast Colorado and associated cyclonic winds. Elsewhere in the figure, we see a tight pressure gradient between this low and the approaching arctic anticyclone as the arctic front noses down the Front Range in the center of the figure. This is where we see the largest discrepancy between the model and observations. Shown in Fig. 3a is the analyzed surface chart valid at the same time. Notice that the modeled position and central pressure of the low correspond extremely well with observations. The observed arctic cold front, however, moved through the state of Colorado to just north of Denver whereas the model advanced the cold front 100 km south of this position. A closer inspection of the RAMS forecast revealed frontal passage approximately 2 h earlier in Denver. Based on a 24-h forecast, the prediction of frontal passage within 2 h is still consid-
The associated 500-mb characteristics were also predicted quite well at this time. Shown in Fig. 2b is the 24-h predicted 500-mb height and vorticity pattern.

Here we see the cutoff low centered over the Four Corners region with the main vorticity maximum on the Colorado–New Mexico border. Comparing with the analysis of the 500-mb heights/vorticity shown in Fig. 3b, we see the analyzed cutoff low over the Four Corners region and associated vorticity maximum on the Colorado–New Mexico border.

Continuing on in time to 1200 UTC 9 March, we see that at 36 h RAMS predicted the surface low to move into east-central Kansas and elongate toward the Great Lakes region (Fig. 4a), while the surface analysis (Fig. 5a) has the surface low analyzed over the center of the state of Kansas. Again, looking at the features aloft, RAMS predicted that much of the energy would be lifting northeastward and weakening as the cutoff became absorbed into the more energetic system to the north. The heights predicted by RAMS shown in Fig. 4b also agree well with the analysis shown in Fig. 5a, including the vorticity maximum predicted and observed over west-central Kansas.

Finally, at 48 h, or 0000 UTC 10 March, the whole system has moved into the Great Lakes region and just beyond the RAMS coarse grid. RAMS continued the northeast track of the storm and propagated the energy out of the model domain in a timely fashion.
As for precipitation, the model predicted the overall pattern well with two maxima predicted and observed. One maximum was predicted along the Front Range from Fort Collins to just south of Denver as shown in Fig. 6. The other maximum was predicted to the east, centered over Imperial, Nebraska (denoted by IML). Shown in Fig. 7 is the observed precipitation valid at 1200 UTC 9 March. The 24-h accumulated liquid precipitation is indicated above and to the right of the station identifier, while the 24-h snowfall is shown below and right of the identifier, and lastly, the 12-h accumulated liquid precipitation is shown in the lower left. All totals were reported at the 1200 UTC reporting time. Through direct comparison of these two figures, we can see many stations that are forecast well while other single station predictions were as much as 100% in error. The biggest discrepancies between modeled and observed precipitation amounts are associated with the southern extent of the precipitation. The observations showed a dramatic gradient in precipitation from Colorado Springs (COS) (2.72 cm) to Pueblo (PUB) (0.30 cm) and, likewise, from Imperial (IML) (2.54 cm) to Goodland (GLD) (0.05 cm). RAMS predicted a sharp gradient in precipitation as well, but was shifted further south on a line from Trinidad (TAD) to Garden City (GCK). The errors in the precipitation forecast can be explained, at least in part, through the use of the crude precipitation scheme and also the embedded convection, which this RAMS configuration could not model. In fact, most of Colorado Springs' precipitation was convective in nature as they reported 2.24 cm of precipitation during the 3 h of thundershowers and snow pellets prior to 0000 UTC 9 March. Improving the predicted precipitation by using a convective parameterization was not attempted; however, a more complete precipitation scheme was subsequently incorporated into the model.

Fig. 5. (a) NMC surface and (b) LFM 0-h 500-mb heights (m)/vorticity ($\times 10^{-5}$ s$^{-1}$) analyses valid 1200 UTC 9 March 1992.
3) ADDITION OF MICROPHYSICS

The microphysics option of RAMS, described in Cotton et al. (1986) and Flatau et al. (1989), accounts for many of the atmospheric processes deleted by the crude "dump bucket" precipitation scheme mentioned earlier. For instance, latent heat release, nucleation processes, ice phase precipitation physics, and evaporation are all handled by the inclusion of RAMS's microphysics option. This option includes five different species that may be individually activated for any given simulation: rain, snow, pristine ice crystals, aggregates, and graupel. Of these, all except graupel were activated for the simulation discussed. Pristine ice crystal mixing ratio and concentration were predicted but all other species' mixing ratios and concentrations were diagnosed from their characteristic diameters. As mentioned earlier, this option could not be afforded when running on the workstation that was available to this project. A new, computationally faster microphysics module, along with a faster workstation allowed use of the bulk microphysics beginning in the fall of 1993.

Addition of the RAMS microphysics option produced some surprising improvements. The mean sea level pressure, surface wind vectors (shown in Fig. 8), and surface temperature gradient (not shown) indicate that the cold front originally forecast south of Colorado Springs was just south of Denver at 0000 UTC 9 March. The center of the low pressure lowered by 2 mb and shifted slightly west; however, the cold front propagated more slowly agreeing more with observations. Perhaps the latent heat released triggered additional upward motion and slowed the progress of the surface convergence and associated cold front. Second, improvements were noted in the low-level wind field.

Lastly, as anticipated, improvement in forecast precipitation was achieved through the addition of microphysics. The RAMS-predicted total precipitation including snow, rain, aggregates, and pristine ice crystals through 36 h is shown in Fig. 9. Notice that the southern extent of precipitation now agrees more closely with observations (Fig. 7), particularly from COS to GLD. The forecast accumulation at COS was the worst single-station forecast precipitation amount as RAMS predicted only 0.25 cm and they received 2.72 cm. As mentioned earlier, however, 2.24 cm of that amount was mainly due to convection, and COS reported only 0.48 cm of precipitation after the convective component had ceased, or at least subsided.

Note the differences between the predicted precipitation in this simulation and the precipitation from the "dump bucket" scheme shown earlier in Fig. 6. The maxima in southwest Colorado (San Juan Mountains) and the central mountains east of Grand Junction (denoted by GJT) were the result of snow during the first 24 h of the simulation and were also reflected in the original real-time forecast. These maxima were
supported by "SNOTEL" (see Doesken and Schaefer 1987) measurements of: 1.78-cm liquid water equivalent at Wolf Creek Pass in southwestern Colorado; 1.78 cm in the center of the state; and 2.03 cm about 100 km due west of DEN. The minimum due west of FCL was also supported by a SNOTEL site at Columbine that reported only 0.25 cm of liquid equivalent precipitation. SNOTEL observations are not as reliable as SAOs since they are taken at varying times and also not taken immediately when precipitation ceases. Nonetheless, measurements are taken daily at roughly 1400 UTC and are included here for comparison purposes since a lack of observational data exists in the Colorado mountains.

The precipitation along and east of the 105th meridian occurred during the 12-h period from 0000 to 1200 UTC 9 March. This is also evidenced by a time series plot of precipitation for a grid point close to Denver (see Fig. 10). It is shown here that onset of precipitation occurred with frontal passage between 22 and 24 h. RAMS predicted the precipitation to begin as rain in Denver and continue to 28 h or 0400 UTC 9 March, totaling 1.4 cm before changing to snow. The forecast snow continued through 36 h or 1200 UTC 9 March with liquid water equivalents equaling the rain accumulation of 1.4 cm. Denver's FAA surface airway observations (SAO) reflected rain showers from 2200 UTC 8 March to 0050 UTC 9 March with an abrupt changeover to snow at 0056 UTC. The SAOs are plotted for the 24-h period beginning 1200 UTC 8 March and ending 1200 UTC 9 March in Fig. 11 along with the companion RAMS forecast plotted in a similar manner. Here we see the reason why RAMS mistimed the changeover to snow by 3 h. RAMS-predicted surface temperatures were 34°F and 32°F at 0000 and 0400 UTC, respectively, while observed temperatures were 32°F and 30°F. RAMS did not predict temperatures to fall rapidly enough during this period, which resulted in a delay in the onset of the changeover from rain to snow.

Summarizing briefly, it was shown that the overall forecast was improved through the addition of the RAMS microphysics option. In particular, features like timing of the arctic cold front, forecast precipitation, and low-level wind prediction reflected dramatic improvements from the simulation using the crude precipitation scheme. The trade-off with the model configuration using the microphysics option is that a faster workstation or clusters of workstations, or a faster microphysics module (see below), must be utilized in order to attain real-time forecasts.

b. Comparison with the NGM forecast of the 8–9 March 1992 blizzard

The NGM model has a rather well-known bias for these type storms along the Front Range in which the
surface low is moved too fast and too far north, in conjunction with an arctic front being too far north. For the 8–9 March simulation initialized at 0000 UTC 8 March, the north bias is evident, not just at the surface, but aloft too. The 24-h NGM forecast valid 0000 UTC 9 March is presented in Fig. 12. The NGM model predicted the surface (part a) low at the Colorado-Kansas-Nebraska border and the 500-mb (part b) cutoff low directly over Denver, Colorado. Recall the analysis shown earlier, which showed the 500-mb cutoff over the Four Corners and the surface low to the south and east of Colorado Springs. This trend continued into the 36-h NGM forecast as these same features were predicted too far north and east. A statistical analysis of the NGM and RAMS forecast for this case will be discussed in the next section.

4. Statistical verification

Because of the difficulty of obtaining mesoscale resolution surface precipitation data over the Colorado Rocky Mountains, it was decided to do the first stage of statistical verification evaluation with the MAPS meteorological data. For simplicity, RAMS 12-, 24-, 36-, and 48-h forecasts were verified against the RAMS initial data fields that were valid at the forecast time. Unfortunately, the initialization procedure using the 60-km grid spacing MAPS analyses was only performed on the coarse grid (100 km spacing) and then interpolated to the 25-km-spaced fine grid. This
• The testing procedure assesses the probability that a predicted pattern could occur by chance alone while providing a quantitative agreement measure of forecast skill.

The agreement measure, $\rho$, is given by $\rho = 1 - \frac{\delta}{\mu_\delta}$, where

$$\delta = \frac{1}{n} \sum_{i=1}^{n} |y_i - \hat{y}_i|$$

is the average absolute difference between $n$ observed and predicted value pairs, $y_i$ and $\hat{y}_i$, respectively, for $i = 1, \ldots, n$; and

$$\mu_\delta = \frac{1}{n!} \sum_{j=1}^{n!} \delta_j$$

is the average of all possible $n!$ pairings with $y_1, \ldots, y_n$ in a fixed order and $\hat{y}_1, \ldots, \hat{y}_n$ permuted in all $n!$ possible ways. Thus $\delta$ is one value among the $n!$ $\delta_j$'s. If the agreement is perfect, then $y_i = \hat{y}_i$ for $i = 1, \ldots, n$, $\delta = 0$, and $\rho = 1$. Incidentally, $\delta$ has an obvious advantage over the root-mean-square (rms) error given by

$$\text{rms} = \left[ \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \right]^{-1/2}$$

in that it treats the $n$ absolute differences in their natural setting involving a simple Euclidean distance between each observed measure and predicted value pair (rms involves squared Euclidean distances in this context and can be severely influenced by a single extreme difference value). This agreement measure has been used extensively for the development of recent seasonal forecasts of Atlantic basin tropical cyclone activity (Gray et al. 1992, 1993) as well as for numerical model evaluation (Tucker et al. 1989).

Using MRBP, eighty-two 12-h, sixty-five 24-h, forty-five 36-h, and thirty-four 48-h forecasts were analyzed for the 1991–92 winter season. Only single variant analysis was performed for temperature, geopotential heights, pressure, relative humidity, and winds at each model level. Note that not all cases were in the verification pool because in some cases only partial or no verification data were received.
The results showed that temperature and geopotential heights agreed best with the analyses, exhibiting agreement measures (similar to correlation coefficients) of 70% to 80% for most of the troposphere. Temperature errors increased markedly in the upper troposphere due to the poor resolution of the tropopause in RAMS (1000-m spacing there). Agreement measures for relative humidity through most of the troposphere were less, typically ranging from 30% to 50%. Agreement measures for wind speed and direction ranged from 40% to 50% in the lower troposphere to 65% to 75% in the upper troposphere. Showing the impact of verifying fine-resolution forecast data against coarser-resolution (and smoothed) MAPS analysis, the agreement measures degenerated by 10% to 20% on the fine forecast grid compared to the coarse grid.

As expected, the agreement measures all decreased by about 5% to 10% in the 24-h forecasts compared to the 12-h forecasts. This trend continued through the 48-h forecast period with agreement measures ranging from 10% less for temperature to 25% for winds compared to the 12-h forecasts.

As for the 8–9 March 1992 blizzard discussed previously, the MRBP analysis for the 24-h forecast beginning 0000 UTC 8 March showed that RAMS clearly outperformed the NGM model. Agreement measures for mean sea level pressure were 0.78 for RAMS and only 0.65 for the NGM. For low-level temperatures, RAMS had 0.84 agreement measure while the NGM had 0.78. Relative humidity agreements were 0.51 for RAMS and 0.36 for the NGM. The higher agreements in the RAMS simulation also held for the u and v components, speed, and geopotential heights as well.

5. What will the future bring?

As we have shown, mesoscale numerical prediction over limited area domains is possible on Reduced Instruction Set Computer (RISC) workstations. We also showed that the addition of microphysics enhanced the forecasting performance of the model. Thompson (1993) also found that the addition of a cloud radiation parameterization scheme enhances predictions of surface temperatures. Unfortunately, the addition of these physical routines adds to the computer time needed for a forecast, requiring the most advanced workstations available in order to achieve wall-clock performance sufficient for real-time forecasting.

There are several solutions to this problem, however. First of all, one can alter, and “engineer” the physical modules so that they require less computer time. For example, a new cloud microphysics module has been developed for RAMS that is based on use of analytical solutions to the collection equation (see Verlinde et al. 1990), and, with the use of lookup tables, this module is more than five times faster than the older module, which uses less accurate accretion approximations to the collection equation. This module is now in its “beta” test phase. Likewise, a new cloud radiation scheme is now being coded that uses the two-stream approximation for both shortwave and longwave radiation, which we expect to be much faster than the old Chen and Cotton (1983) scheme.

Second, at the beginning of this research (~2 years ago), the workstation available to the real-time forecasting project was one of the highest-performance workstations on the market. It is now some factor of 5 or more slower than RISC processors that can be purchased for under $30,000! Thus, advances in workstation performance already allow the use of expanded physics or higher spatial resolution and major advances in performance are expected in the next few years.

Finally, software is being written for RAMS, MM5, University of Oklahoma Advanced Regional Prediction System (ARPS), and has already been written for the Penn State/NCAR MM4 that will allow computations to be performed on clusters of workstations running a model in parallel. Clusters of 4, 8, and even 64 workstation processors can now be purchased. Using relatively inexpensive networks, one can obtain performance gains relative to a single processor of 3.8 on a cluster of four workstations and 4.2 on a cluster of five workstations. Recently, Wightwick and Leslie (1992) reported performance gains of 11 relative to a single process on a cluster of 16 workstations running a new limited area model with 20-km grid spacing. Thus, one can design a customized, stand-alone, mesoscale forecast system that can meet the needs of a variety of forecast applications. Currently, the biggest limitation in performance of running clusters of a workstation is the communication bottleneck between processors. This bottleneck can be minimized by using high-performance switches and communication networks, and by optimizing code so that communication is minimized.

Four-dimensional data assimilation can also enhance mesoscale numerical forecasting performance. Using techniques such as nudging (Anthes 1974; Hohe and Anthes 1976; Kuo and Guo 1989), adjoint or optimum control theory (Le Dimet and Talagrand 1986; Thacker 1988a,b; Derber 1989; Thacker 1989), or Kalman filters (Kalman 1960; Thacker 1987), there is the prospect of assimilating asymptotic data such as satellite, Doppler radar, ground-based radiometers, ACARS, and wind profilers into a mesoscale forecast model. The assimilation routines could either be fully
automated or use human–machine interactions on a dedicated assimilation workstation. Data assimilation on limited domains such as illustrated here would help in short-range 1- to 12-h forecasts, but for longer-period forecasts, the assimilation domain would have to be comparable with the coarse-grid domain in our prototype forecasts.

6. Applications and potential problems

There are numerous applications of such a workstation-based forecast system. First of all, one could imagine each National Weather Service Forecast Office (WSFO) to have its own mesoscale model that could provide forecast products that are unique to that region. A negative feature of such a scenario is that the NWS would have to maintain software for each WSFO. A way to minimize that impact, however, would be to use a common source code for all WSFOs but have different configurations or options of that code in use at the various WSFOs. Thus, a region frequented by fog may have a grid configuration that is optimum for fog prediction while in another region, lake effects may be more important, so that a grid resolving those lake influences would be more desirable.

Other applications include

- support of Federal Aviation Administration (FAA) operations including mesoscale forecasts of icing conditions, aircraft weather hazards, ceilings, visibility, and turbulence;
- use in agricultural forecasts of maximum/minimum temperatures, frost/freeze warnings, and evapotranspiration/precipitation forecasts for irrigation scheduling;
- special forecasts in support of military operations; and
- mesoscale forecasts of air quality and emergency response.

Warner and Seaman (1990) pointed out the educational use of numerical mesoscale forecasting. Specifically, students can be involved in the running of models, the analysis and display of model data, and critiquing of model output products. Moreover, any college or university that can support a high-performance workstation and has access to a mesoscale model code and gridded NMC analysis and forecast products can perform prototype real-time forecasting. In addition to Warner and Seaman’s use of MM4 on a mainframe computer and CSU’s use of RAMS on a workstation, routine mesoscale forecasts are being done on a workstation at the University of Wisconsin under the direction of Greg Tripoli.

There is also a largely untapped opportunity for the private sector. Mesoscale numerical forecasts made on high-performance workstations could be tailored to provide products that are useful to industries such as transportation, recreation, and construction.

At this point we have not mentioned the application of workstation-based mesoscale numerical prediction to severe storm forecasting. This is because this very challenging problem pushes the state-of-the-art of numerical prediction to its limits. Certainly, simulations of individual supercell and multicell thunderstorms and squall lines is possible on workstations with grid spacing on the order of 1.5 to 2 km over domains on the order of 100 km x 100 km. These simulations, however, take about five times real time to perform on the highest-performance workstations. Even modest clusters of workstations (e.g., four to eight processors) will not bring us into a real-time forecasting level of performance. It is very likely, however, that RISC workstation performance will advance fast enough that in three to five years the required performance level will be achieved. Moreover, if clusters having on the order of 64 processors become available with performance gains in excess of 50 times single-processor performance, then real-time explicit simulations of severe storms is possible. This may even happen in the next year or so!

The problem of numerical forecasting of severe storms is not solved simply by having the required computer processing power at one’s fingertips. New developments in human–interactive model storm initiation or four-dimensional data assimilation are also required. Nonetheless research is being done in this area and it is possible that workstation-based severe storm forecasting could be a reality in the next three to five years.

This brings up an interesting social/political problem. The primary responsibility of NMC is to produce numerical prediction guidance for the entire United States. Considering the expected advances in multiprocessor supercomputers in the next three to five years, we can anticipate NMC’s operational forecast models to have grid spacing on the order of 5 to 10 km, which is not sufficient to resolve explicitly deep convection (e.g., without a cumulus parameterization scheme). On the other hand, we noted above that it is quite conceivable that on that time scale, a television station, for example, could be running their own mesoscale forecasts with 1.5- to 2-km grid spacing over the region of coverage of their station and producing animated, three-dimensional displays of predicted supercells and other severe thunderstorms. Even though the NWS may release the only official severe weather advisories, to whom do you think the person-on-the-street will pay the most attention? Moreover,
as pointed out by Bill Kuo (personal communication), one could imagine a scenario where in a major metropolitan area, channel 4 produces animated forecasts products from MM5, channel 6 produces different results running RAMS, and channel 10 produces products from ARPS, that differ from the other two; a very confusing situation indeed!

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