A PERFORMANCE EVALUATION OF THE NGM AND RAMS MODELS FOR THE 29–30 MARCH 1991, COLORADO FRONT RANGE STORM

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Abstract

This study investigates the performance of each the National Weather Service, National Meteorological Center's Nested Grid Model (NGM) and Colorado State University's Regional Atmospheric Modeling System (RAMS) for the 29–30 March 1991 Front Range storm. Through this investigation, a better understanding of both models' efficiency and limitations can be assessed as they simulate the multicomponent nature of winter storms in Colorado's mountainous terrain. In addition, this study has focused much of its attention on initialization procedures in RAMS, and how these procedures affect model output.

In a RAMS control run, which was set-up to mimic NGM's grid structure, it was evident that RAMS was able to outperform NGM for this one storm. In six subsequent RAMS sensitivity simulations, it became clear that it is extremely important for the model to be initialized with realistic topography and surface properties, such as a reasonable soil temperature profile. To date, Colorado Front Range winter storms still pose difficulties in forecasting snowfall amounts and the presence of supercooled liquid water aloft. This RAMS simulation has begun to focus attention, at least from a modeler's perspective, on what parameters are of critical importance in these simulations and what parameters are of lesser significance.

1. Introduction

The National Weather Service, National Meteorological Center's Nested Grid Model (NGM) is one of the most widely used meteorological models since it is used by both operational forecasters and research scientists. With an 80 km × 80 km horizontal grid spacing, and with 16 vertical levels ranging from the surface to a height of about 18 km, the model's resolution is too coarse to resolve many of the mesoscale circulations that develop over the mountainous regions of the western U.S.A. For example, along the Colorado Front Range during winter precipitation events, it is well known that linear shaped snowbands (100 km × 25 km) often develop and are responsible for moderate to heavy snowfall totals in select areas (Rasmussen et al. 1990; Wesley 1991; Wesley et al. 1990). With NGM's coarse resolution these mesoscale snowbands remain unresolved and often lead to erroneous forecasts of snowfall amounts.

Fully aware of the limitations of such a low resolution model, we decided to compare and contrast the output of Colorado State University's Regional Atmospheric Modeling System (RAMS) to that of the NGM, in order to gain new insight into the importance of realistic topography, initialization of surface fluxes, and microphysics in these types of models. We selected the 29–30 March 1991 storm as a case study because the NGM greatly over-predicted the extent and amount of snow that fell along the Colorado Front Range. Late in the evening of 28 March, this particular storm had all of the traits of a deep, cyclonic storm that would have produced widespread and moderate snowfall across the area. At 0000 UTC on 29 March, a 500-mb low was positioned over the Texas panhandle (Fig. 1). Over the next 12 hours, a 500-mb low developed over southwest Colorado (Fig. 2a), while a 700-mb low formed over northeast New Mexico both in association with an intensifying disturbance northwest of Colorado shown in Fig. 1. In addition, there was a surface high over the upper Great Plains that by 0000 UTC was causing northeasterly flow of colder air into the Front Range. NGM's 24 and 36-hour forecasts, made at 0000 UTC on 29 March, predicted moderate amounts of snowfall (10 to 20 cm) from northern Wyoming to northern New Mexico (Figs. 2 and 3), including much of the central Rockies. Figure 4 shows total precipitation for the storm across the Colorado region. It is evident that there were select areas which received 2.0 cm or more of water equivalent precipitation, but those regions were of very limited area, certainly not to the extent and amounts predicted by the NGM.

Direct comparison between the two models is limited since the RAMS model is not a true forecast model beyond the first 12 hours of the simulation. This is due to the fact that RAMS' lateral boundaries are nudged every 12 hours to the observed National Meteorological Center's analyzed fields through the isentropic analysis package. However, the nudging can be adjusted so that the observed fields have a minor influence on the interior of the model domain.

The RAMS model has been used previously to study winter precipitation events along the Front Range. Wesley (1991) simulated both deep cyclonic and shallow anticyclonic upslope events. He found that topography plays a major role in the distribution of snow along the Front Range due to small-scale orographic lift as well as cold air damming.

Boatman and Reinking (1984) found that in the case of an arctic outbreak; "upslope clouds resulted from topographically induced upward motions associated with low-level easterly flow." The arctic air mass is often only about 100 mb deep, and the upslope clouds form at the top of the cold airmass. A well-known shortcoming of NGM, as reported by Junker et al. (1989), is its inability to accurately predict the evolution of low-level arctic air masses over the High Plains.

Abbs and Pielke (1987) simulated two upslope snowstorms with a model that was a precursor to RAMS. They concluded that the effects are strongly dependent on the orientation of the prevailing wind with respect to terrain orientations. Hence, southeast winds that descend from the Palmer divide into Denver often result in little snowfall; northeast winds, however, have to move upslope towards Denver and often are associated with larger amounts of snowfall.
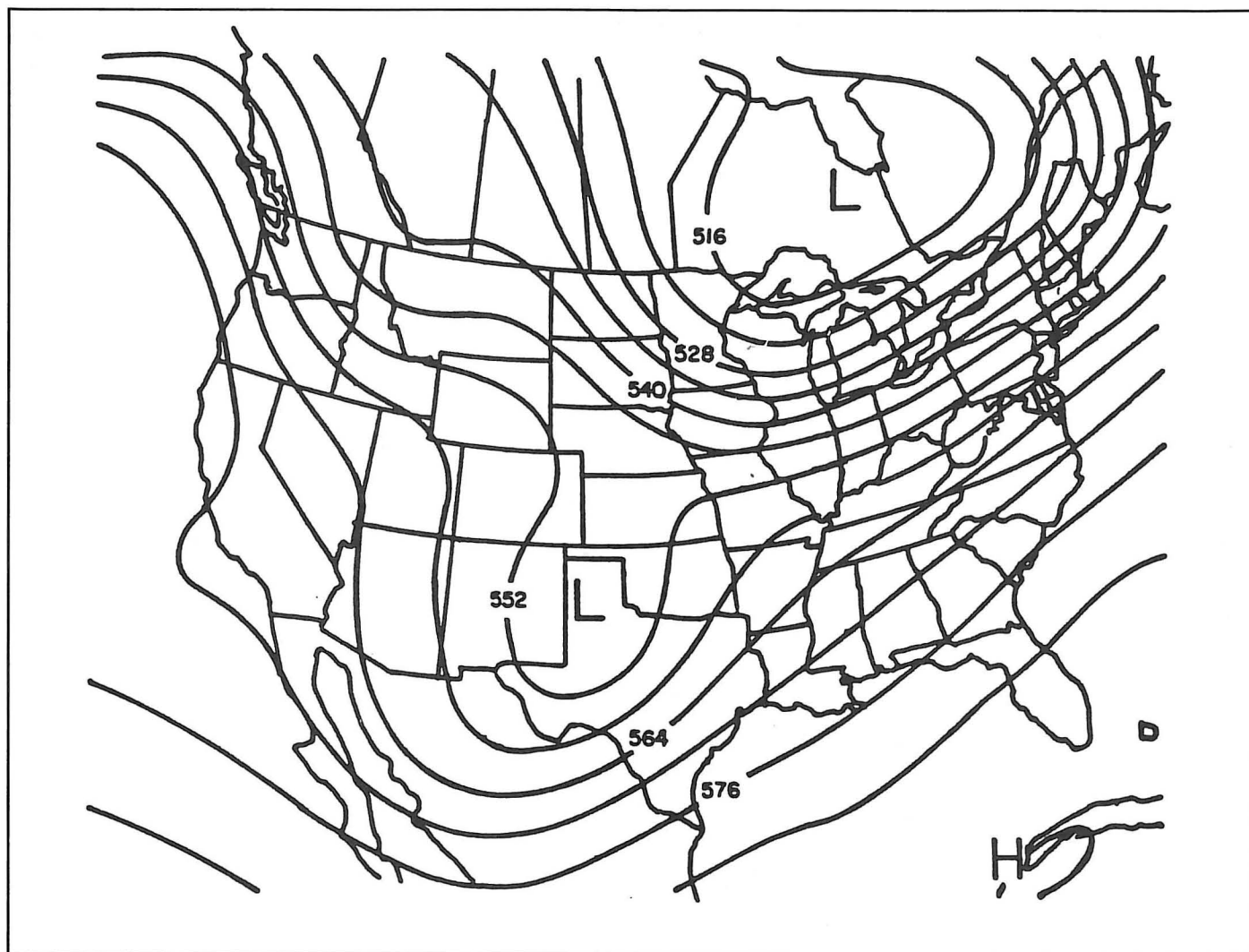
Fig. 1. 500-mb height field at 0000 UTC 29 March (60 m contour interval).

Dunn (1987), as well as Wesley and Pielke (1990), have observed and noted the significance of a well-defined convergence zone to the east of the foothills as easterly flow has to ride up and over the cooler air trapped along the Front Range. Clouds produced at this convergence zone often propagate westward towards the foothills where they act as seeder clouds for the lower lying feeder clouds.

Recently, Thompson (1993) has completed real-time simulations of Colorado weather with a simpler form of RAMS and compared the results with both the National Meteorological Center's NGM and ETA model predictions.

2. RAMS Set-Up

The RAMS model (Pielke et al. 1992) was set-up with the intent of mimicking NGM as close as possible. All simulations were run using RAMS version 2c, with variable initialization. Table 1 summarizes the pertinent model parameters used in these simulations. The domain is shown in Fig. 5. For topography we utilized the United States Navy 10-minute terrain data set (Fig. 6). It should be mentioned that NGM also used the Navy 10-minute terrain data (Hoke 1989), however, their smoothing routine reduces the height of the Rocky Mountains

to about 2400 m, while RAMS' silhouette averaging produces a barrier of up to 3200 m in height. We will address this problem in Section 4.

We utilized a multi-level soil parameterization developed by Tremback and Kessler (1985), whereby the user specifies the number of soil levels, soil moisture, and temperature for various types of soils. For all of the simulations presented in this paper we felt that loam was probably the most representative considering that our domain stretched across most of the North American continent. The soil module is initialized horizontally homogeneous across the entire land mass. It is possible to make the soil parameters grid dependent, but since regional data on soil properties is scarce, we felt that a horizontal homogeneous initialization was necessary. In any case, this is a winter study and the influence of soil moisture was originally expected to be minor.

The RAMS version 2c microphysics module uses a bulk parameterization which assumes that rain water, pristine crystals, snow, graupel, and aggregates may be represented by a continuous specified size distribution (Flatau et al. 1989). Diagnostic concentrations were used for all species except pristine crystal which uses a prognostic scheme. Each species can acquire mass through vapor condensation/deposition, self-
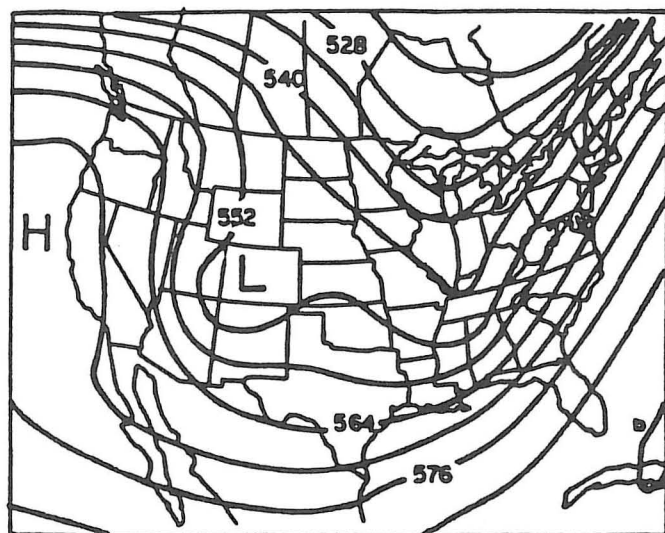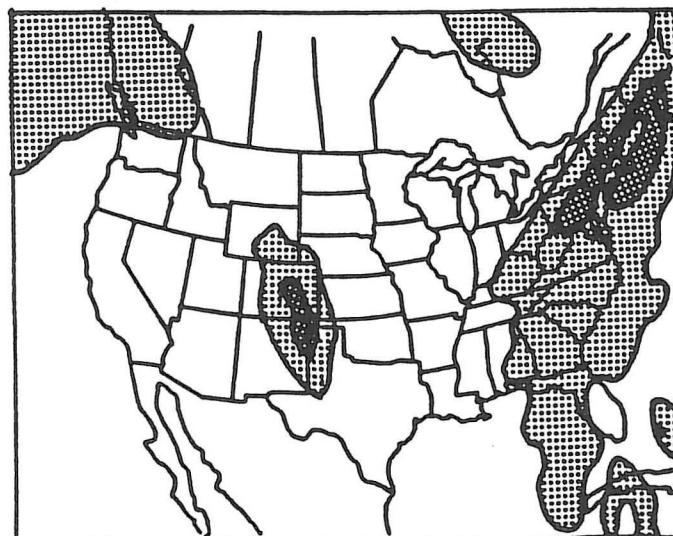
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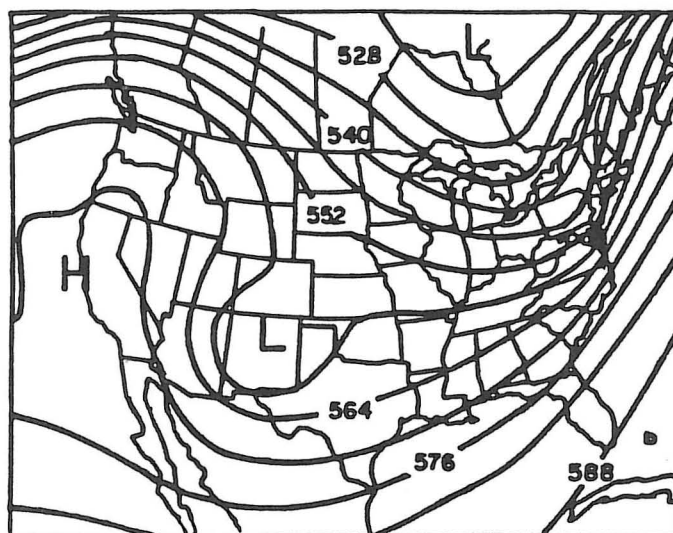
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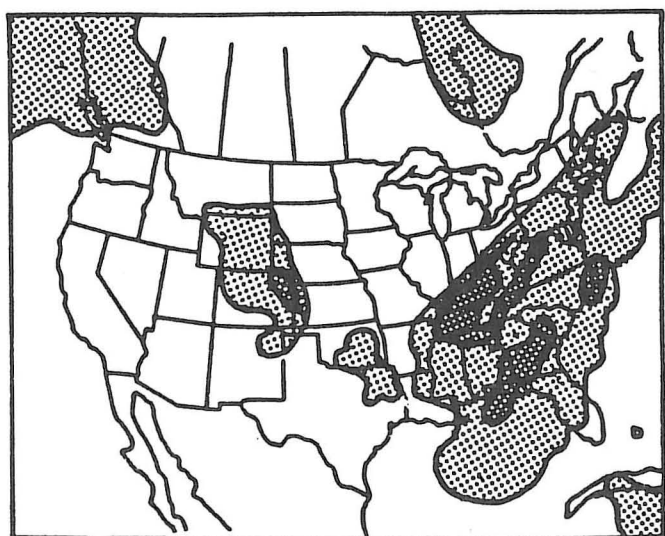
(b)

(b)

Fig. 2. NGM 24-hour forecast valid 0000 UTC 30 March for (a) 500-mb height field (60 m contour interval) and (b) precipitation (light stipple − 0 to 0.5 inches, dark stipple − 0.5 to 1.0 inches).

Fig. 3. NGM 36-hour forecast valid 1200 UTC 30 March for (a) 500-mb height field (60 m contour interval) and (b) precipitation (same units as in Fig. 2).

collection, or interaction with another species. The model predicts the mixing ratios of each species, while the distribution of a particular species is diagnosed. In all of our simulations we defined the minimum pristine crystal mass to be 1.0×10^{-11} kg, cloud condensation nuclei concentration of 3.0×10^5 per liter, and a homogeneous nucleation temperature of 233 K.

3. RAMS Results

We began all simulations at 0000 UTC 29 March and let them run for 36 hours. For our control run we utilized all six water species in the microphysics module. Figure 6 shows the evolution of RAMS surface winds (200 m AGL). Initially, there

is a slight northeast flow (upslope) along the Colorado Front Range, but the upslope is short lived. During most of the period the flow is northwesterly or northerly which is not conducive to snowstorms. Figures 7a and 7b indicate the total accumulation of precipitation after 24 hours and 36 hours. The broad band of precipitation in the Appalachians and Ohio Valley was handled fairly well, except near the RAMS lateral boundary. Figures 7c and 7d show the Colorado region in greater detail. After 36 hours the heaviest precipitation, approximately 2.4 cm, is along the Nebraska, Kansas, Colorado border area, with two smaller maxima centered over the central Rockies and southeast Colorado. It does appear that RAMS greatly overestimated the amount of precipitation that fell in the Nebraska, Kansas,
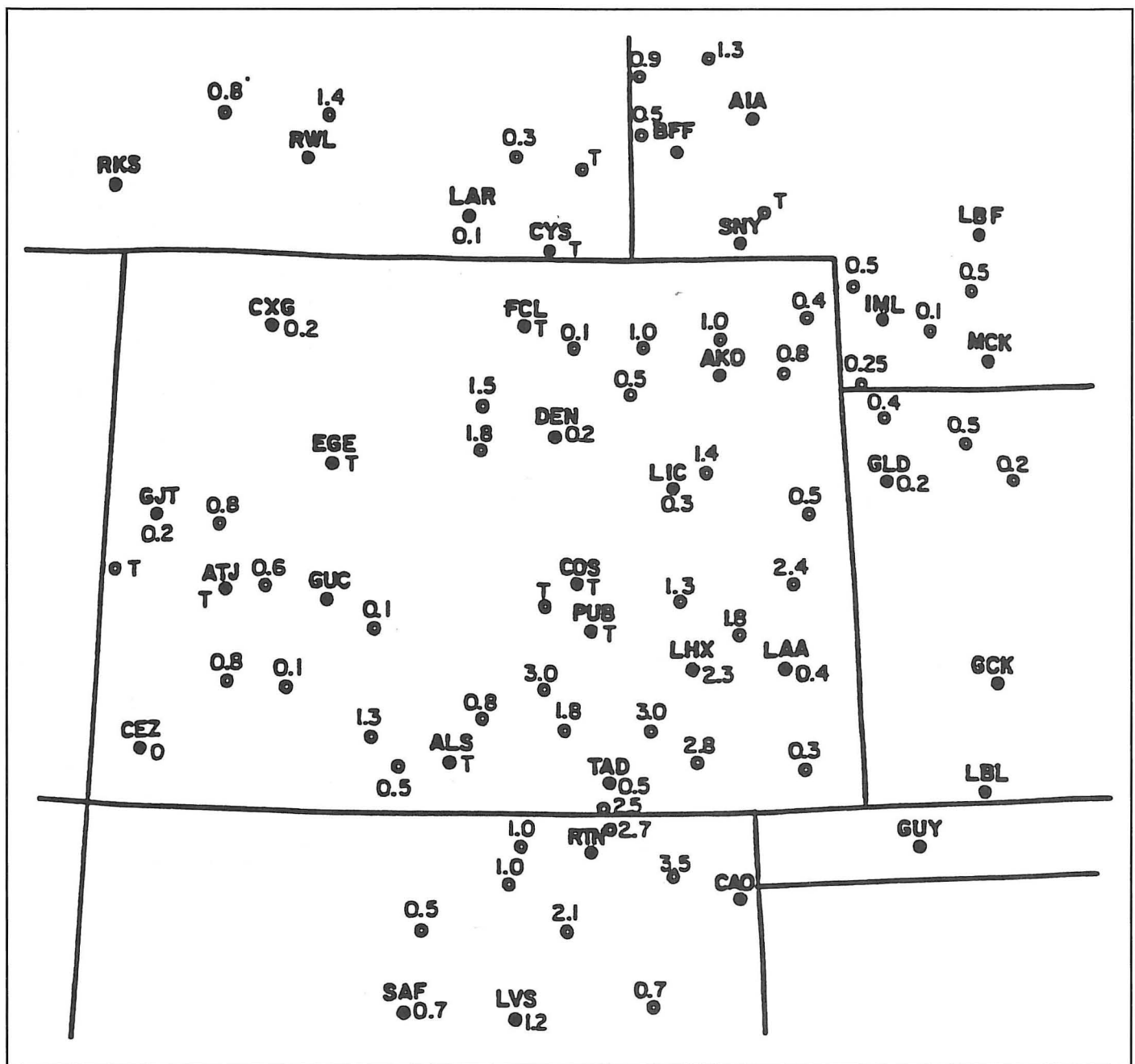
Fig. 4. Storm totals 29–30 March 1991 (cm water equivalent; for unmarked stations, data was not available).

Colorado area by as much as 1.5 cm. We believe that this is due to the fact that model topography is too coarse, with the terrain gradient along the eastern edge of the Rockies extending too far out into Kansas and Nebraska (i.e., the barrier of the Front Range was not realistic).

Figure 8 shows RAMS total accumulated rainfall over the Colorado region. In the Nebraska, Kansas, Colorado maxima, 2.0 cm out of 2.4 cm fell as rain. Observations from this area indicate that what precipitation did fall, fell mostly as rain with small amounts of snow mixed in. In southeast Colorado, however, 0.9 cm out of a possible 1.2 cm fell as rain in the RAMS simulations. However, observations show that in this area most of the precipitation was in the form of snow. The underestimation in snowfall (all species of snow) is due to the

fact that the model surface temperatures are too warm, which we feel is a result of large surface heat fluxes that are generated from a soil profile which is too warm. Over a large domain such as we have, we initialize the soil layer temperatures as offsets from the lowest atmospheric level temperature. If warm air occupies all or a portion of the domain at the onset of the simulation then the soil temperatures will be too warm unless the modeler specifies large temperature offsets, which can only be done if soil temperature data is readily available; otherwise one has to simply guess. We conducted several sensitivity simulations by altering soil temperatures; those results are presented in the following section. In addition, the version of RAMS used in our simulations contains no snow cover parameterization.

Table 1. Model parameters used in RAMS simulations.

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Primitive equations	−Nonhydrostatic
Grid points	−70, 62, 16 in x, y, z
Grid spacing	−80 km in x, y, and variable in z ranging from 200 m to 1000 m
Timestep	−90 seconds
Radiation	−Chen parameterization, updated every 1200 seconds
Top boundary	−Wall at 18,500 m
Albedo	−0.2
Surface Roughness	−0.05 m
Soil Parametrization	−Tremback and Kessler. 11 soil levels
Microphysics	−Explicit
Initialization	−Variable with 12-hour nudging
Diffusion	−Deformation

(a)

Hence, more radiation is absorbed by the soil than actually takes place in areas with some snow on the ground.

Overall, RAMS was able to show some fine structure to the areal distribution of precipitation as well as more representative amounts (except for the problem areas noted previously), which were handled poorly by NGM. Since both models have similar grid set-ups, they both have about the same spatial resolution, we then have to ask why RAMS did somewhat of a better job? We conclude, as discussed in Section 4, that it is a combination of several factors, most importantly terrain representation and low-level flow field representation.

Both models did moderately well in predicting the movement and pressure values of the low that moved from central Wyoming to northeast New Mexico. However, the NGM 0000 UTC 30 March forecast (24-hour forecast) has the low over southwest Colorado, about 150 km too far west and the geopotential heights about 20 to 30 m too low. These 'errors' are not large but do suggest an over-deepening of the low, allowing moisture from the Gulf of Mexico to be advected over the Front Range. NGM predicted vertical velocities of 9 cm s^{-1} over the Front Range while RAMS had half of that value after 24 hours of simulation.

Junker et al. (1989) have documented NGM's difficulty in over-deepening low pressure centers that move eastward out of the Rockies. They also noted that NGM has a cold bias over the Rockies. Cold temperatures in the winter time should lead to higher rates of condensation over and to the east of the Rockies. In addition, Petersen and Hoke (1989) mentioned that NGM's snow cover parameterization was updated once a week (as of winter 92/93 it is updated daily). In the autumn and spring, when the areal coverage of snow can change very rapidly, areas that do not actually have snow cover will then have cooler temperatures in the model, in some circumstances as much as 10°C.

Topography plays a prominent role in the weather of the western USA, such as during Front Range snowstorms (Wesley 1991). Smaller mountain ranges such as the east-west oriented Cheyenne Ridge and Palmer Lake Divide help block cold air as well as provide uplift for mid-level and surface flows. The 10-minute U.S. Naval Terrain Data set used by both the NGM and RAMS is too coarse to resolve either one of those two important features. Figure 9 shows both sets of model topography after smoothing and filtering. There are two important differences between them. First, the height of the Rocky Mountains in the NGM is some 2300 m, while in RAMS it is 3200
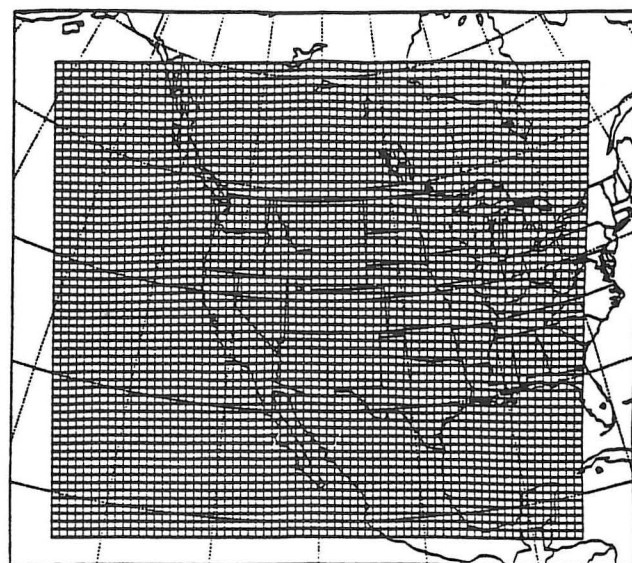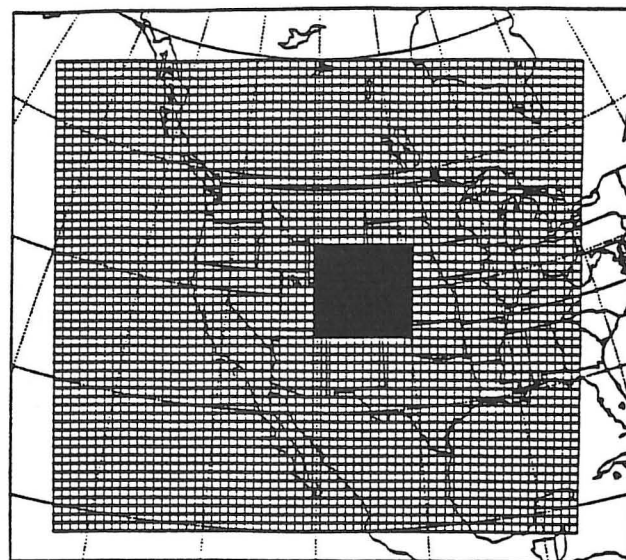
(b)

Fig. 5. RAMS domain (a) coarse grid 80 km × 80 km, (b) addition of fine grid 20 km × 20 km.

m. Hence, a large portion of central and western Colorado lies well above the highest levels in the NGM topography. Secondly, the gradient along the Front Range (eastern slope) is greatly underestimated in both models. However, in the NGM the elevation difference from central Colorado to the Colorado/Kansas border is about 1300 m while in RAMS it is 2000 m. In essence the topography used in the RAMS simulations is much more realistic in terms of absolute height and terrain gradients.
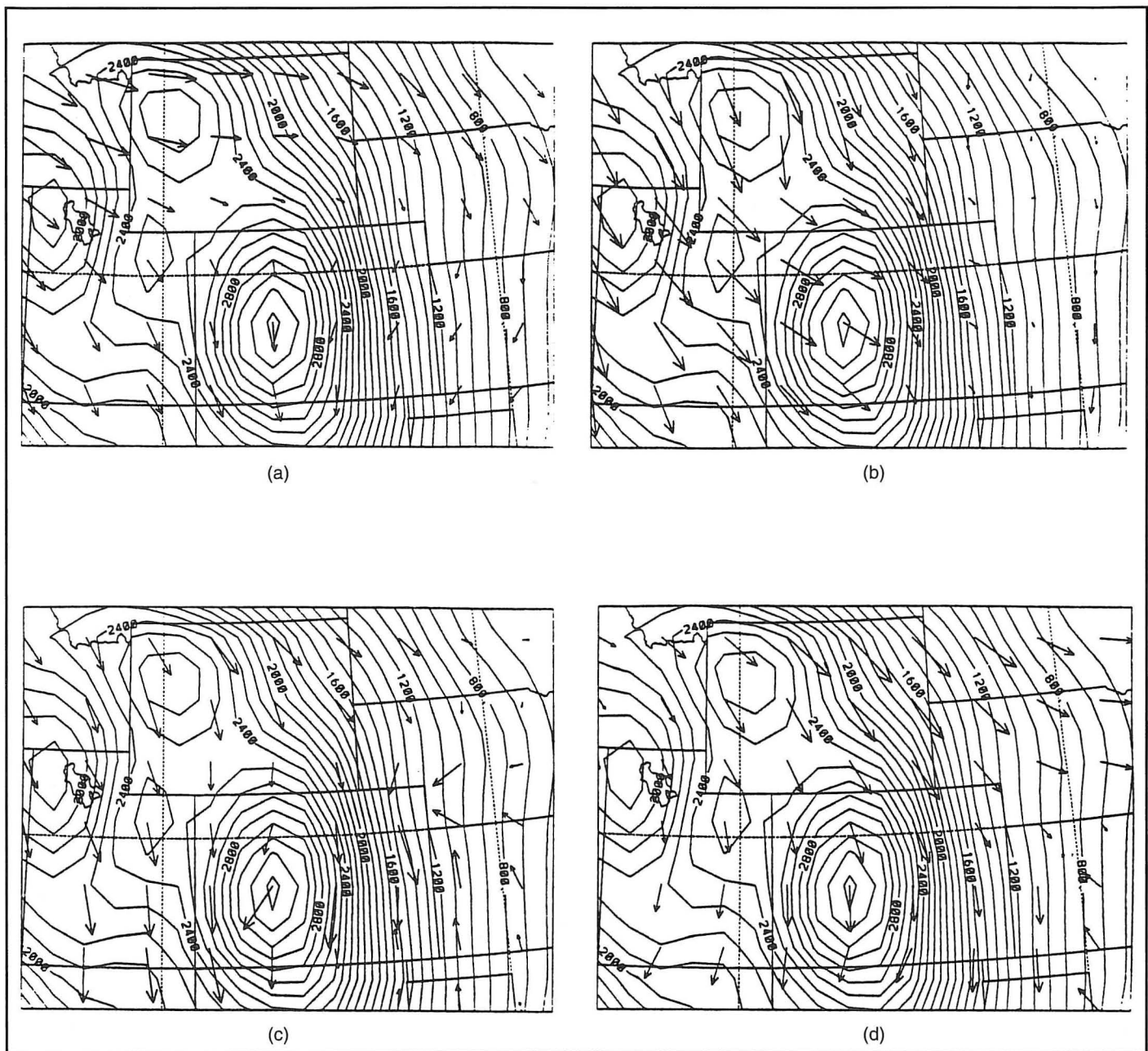
Fig. 6. RAMS surface winds (200 m AGL) for (a) 0000 UTC 29 March, (b) 1200 UTC 29 March, (c) 0000 UTC 30 March and (d) 1200 UTC 30 March. Terrain elevation is contoured in units of 100 m. Wind vector 1 cm long equals 10 m s^{-1}.

4. Sensitivity Simulations

In order to facilitate our understanding and confidence in the RAMS model we have conducted a number of sensitivity simulations, some which have already been briefly discussed. One of our objectives in doing so is to see the sensitivity of RAMS to initial conditions, with the intent of learning how significant each model component (i.e., atmospheric dynamics, surface fluxes, topography) is in creating weather at any given location within the model domain.

We have already noted that RAMS is nudged every 12 hours at the lateral boundaries toward the observed fields. Our first sensitivity simulation was conducted by reducing the weighting function on the lateral five most grid points surrounding the domain. With this reduction in nudging the wind fields and pressure patterns changed very little. In the Colorado region there were up to 5% differences in precipitation (maxima shifted 100 km to 150 km west). This does indicate that the model is doing an excellent job of calculating all fields without having to rely on the nudging to bring it back to what was observed.

Our second sensitivity experiment was to adjust the microphysics module so that the snow species was turned off. This allowed precipitation to fall as one of the following species: rain, pristine crystals, aggregates, or graupel. When compared to the control run the maxima in total precipitation was reduced by 12% and a slight shift in the areal distribution of one of
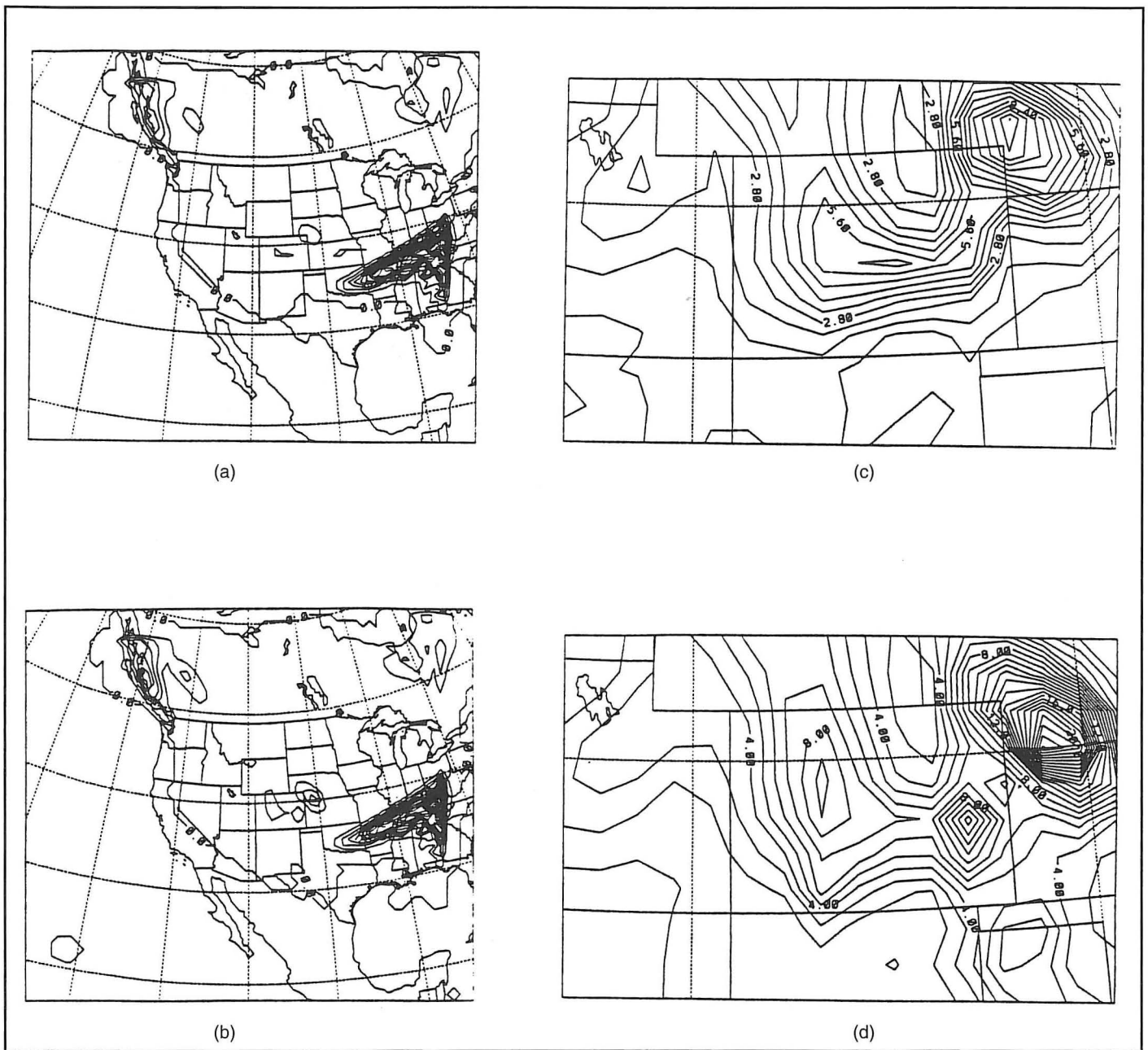
Fig. 7. RAMS total precipitation in mm for 29–30 March 1991 at (a) 24 hours and (b) 36 hours for coarse grid; (c) 24 hours and (d) 36 hours for the fine grid. Contours: 5 mm in a) and b); .7 mm in c); and 1 mm in d).

the three maxima. Concentrations of rain, aggregates, and pristine crystals towards the total precipitation were reduced from the control run but were somewhat offset by an increase in the concentration of graupel. We surmise that the decrease in the total precipitation is due to differences in evaporation and condensation rates between the two simulations.

For a third sensitivity experiment we reduced the temperature of the soils so that the entire 0.5 m deep soil layer was 5 K cooler than in the control run. This had the effect of reducing the total precipitation on the order of 10 mm (42%) at the Nebraska/Kansas/Colorado maxima in better agreement with the observations. The cooler soil temperatures did not cause any significant difference in snowfall totals over the mountains.

These results indicate the influence that surface fluxes have on precipitation processes; a result that we did not originally suspect for a winter storm simulation. Not only is the supply of moisture in many cases determined by surface fluxes, but these same fluxes can alter the dynamics of the atmosphere as well. Lower soil temperatures cause the soil skin temperature to also be lower than it was in the control run. This in turn caused reductions in the amount of moisture that could be evaporated, and reductions in the strength of the parameterized convection. The implication is that one can not simply ignore surface and soil properties as being irrelevant or minor components in simulations of 36- to 48-hour duration even during a winter simulation.
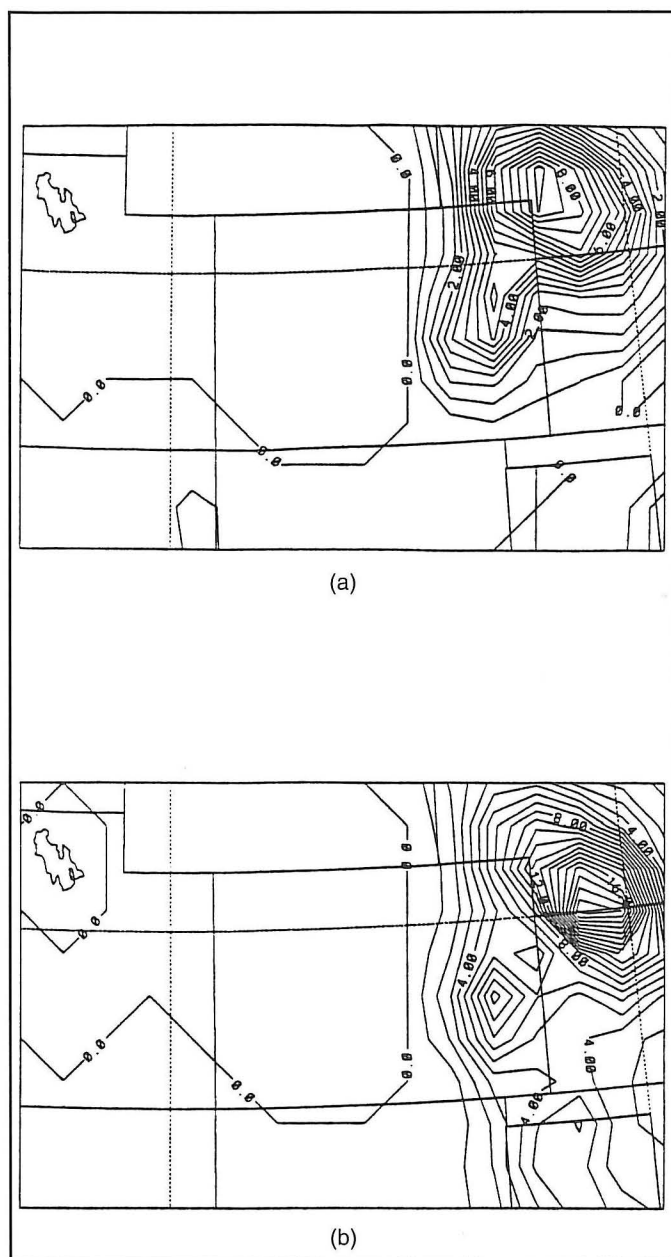
(a)

(b)

Fig. 8. RAMS total accumulated rainfall in contour intervals of 0.5 mm for 29–30 March 1991 at (a) 24 hours and (b) 36 hours.

(a)

(b)

Fig. 9. (a) NGM topography, contours are 100 m and (b) RAMS topography, contours are 200 m.

In the fourth sensitivity simulation we reduced the weighting function in the RAMS topography smoothing routine. This had the effect of reducing the height of the Colorado Rockies from 3200 m to 2600 m. In addition, it reduced the topographic barrier of the Front Range to low-level easterly flow by several hundred meters.

The results show a reduction in the 850 and 500-mb wind speeds. Precipitation totals over the Rockies decreased in this simulation from 9 mm (control run) to 6.5 mm, which was to be expected since there was less orographic lifting of the westerly flow. This brings up the question: how realistic does model topography have to be in order to obtain reliable output? The ideal situation is to have a near perfect terrain representation, but that is highly impractical for numerical models where some type 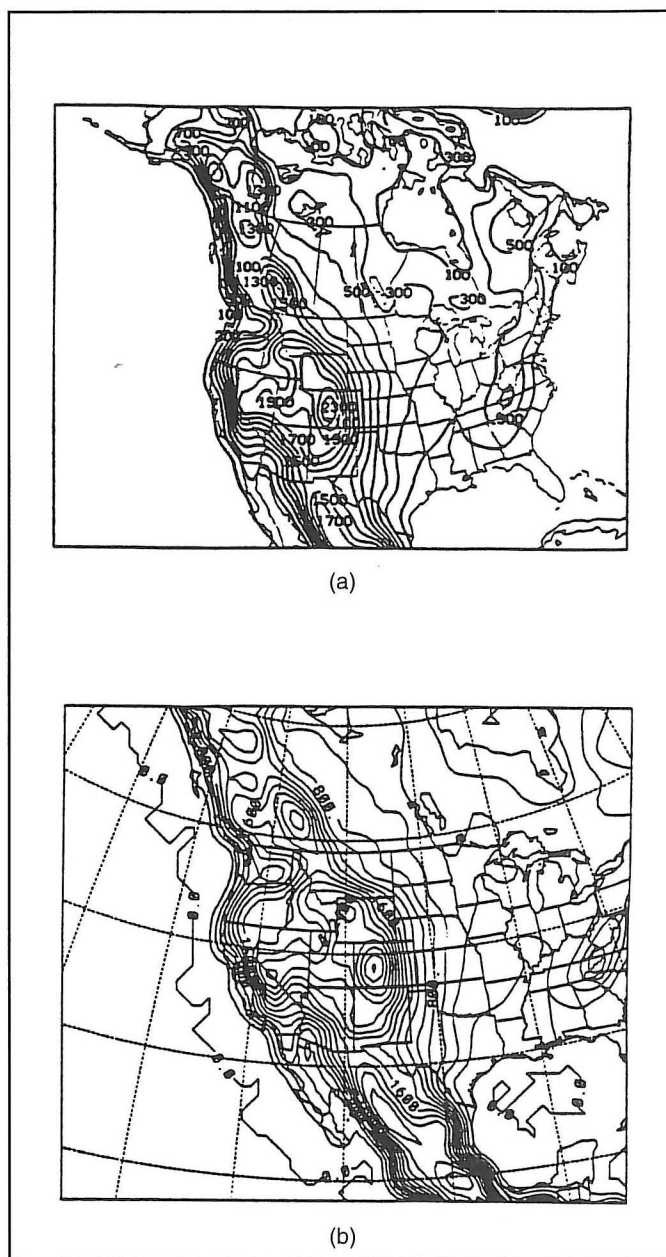of smoothing is required for model stability. For moderate to high resolution simulations over mountainous regions, the terrain should be as close to the real world as is possible. This is one of the major shortcomings of the NGM; the topography of the western half of the North American continent is too idealized to produce reliable precipitation predictions over much of this region.

The fifth sensitivity simulation consisted of an addition of a 600 km by 600 km fine grid with a horizontal grid interval in this region of 20 km, centered over Colorado. We also increased the number of vertical levels from 16 to 29. Figure 10 shows the model topography using the U.S. Navy 10-minute data set. With the addition of the fine grid, the southern Rocky Mountains are much better resolved than the topography used in the control run.
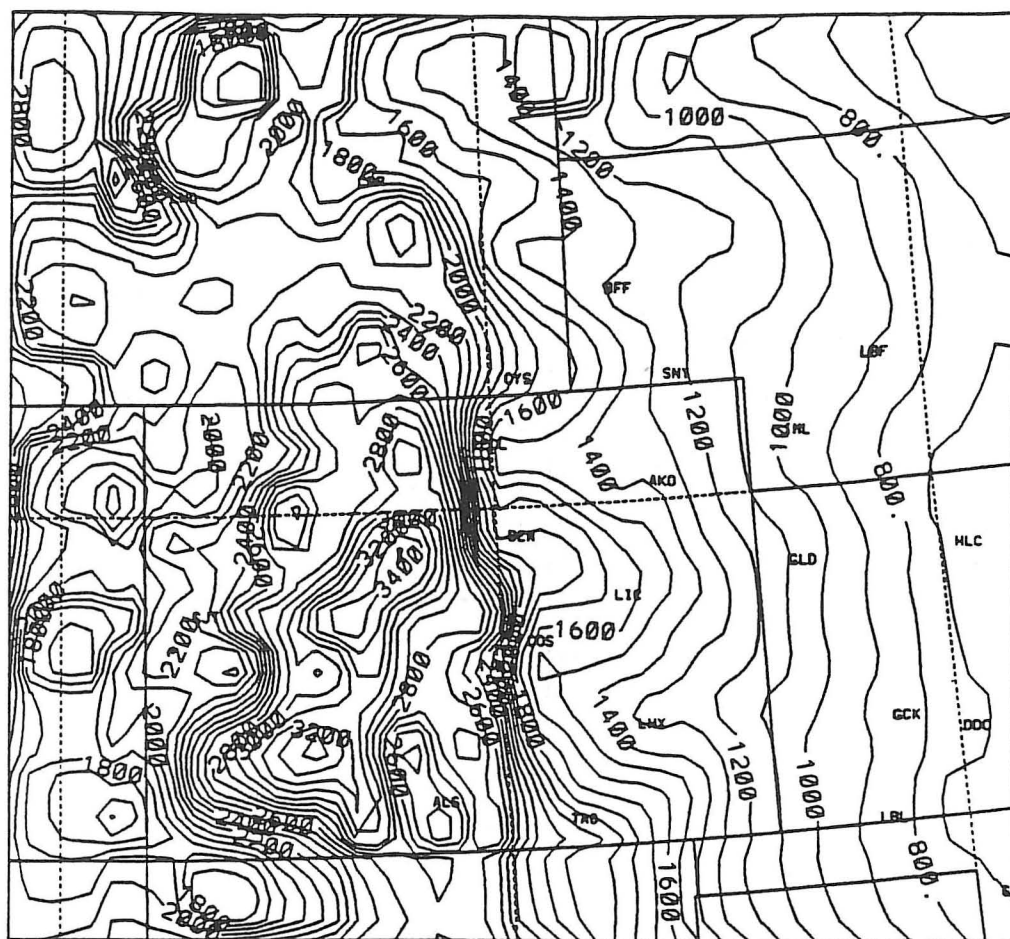
Fig. 10. Topography within fine grid. Contours are 200 m.

In the region covered by the fine grid, results indicate an increase in the resolution of precipitation patterns when compared with the control run (Fig. 7). The area of heaviest precipitation (Fig. 11) in the model is in close agreement to the maxima observed precipitation for this particular storm. In the mountains, RAMS did very well in depicting precipitation, as would be expected with better terrain representation.

5. Conclusions

This study, as well as those of Wesley (1991) and Meyers and Cotton (1992), all indicate that the RAMS model can successfully simulate winter storms in complex terrain.

In essence, RAMS was able to capture the areal distribution of precipitation patterns across the domain, although the amounts of precipitation were consistently less than observed amounts. One advantage of RAMS is the availability of model output at a variety of spatial scales. For example, the model user can specify the area of the plotting routine in order to enhance the resolution displayed in the output, in effect, zeroing in on an area of interest. NGM's plotting is too crude to show much in the way of detail, hence an observer's perception of its output is downgraded.

RAMS is now being utilized by several research organizations that are investigating winter storms along the Colorado Front Range. In the near future the authors are planning to use the model in order to perform some high resolution simulations to investigate the formation and propagation of elongated snow-bands that develop during many winter storm scenarios. Future topics for research include the effect of snow cover on meso-scale circulations during spring snowstorms.

Acknowledgments

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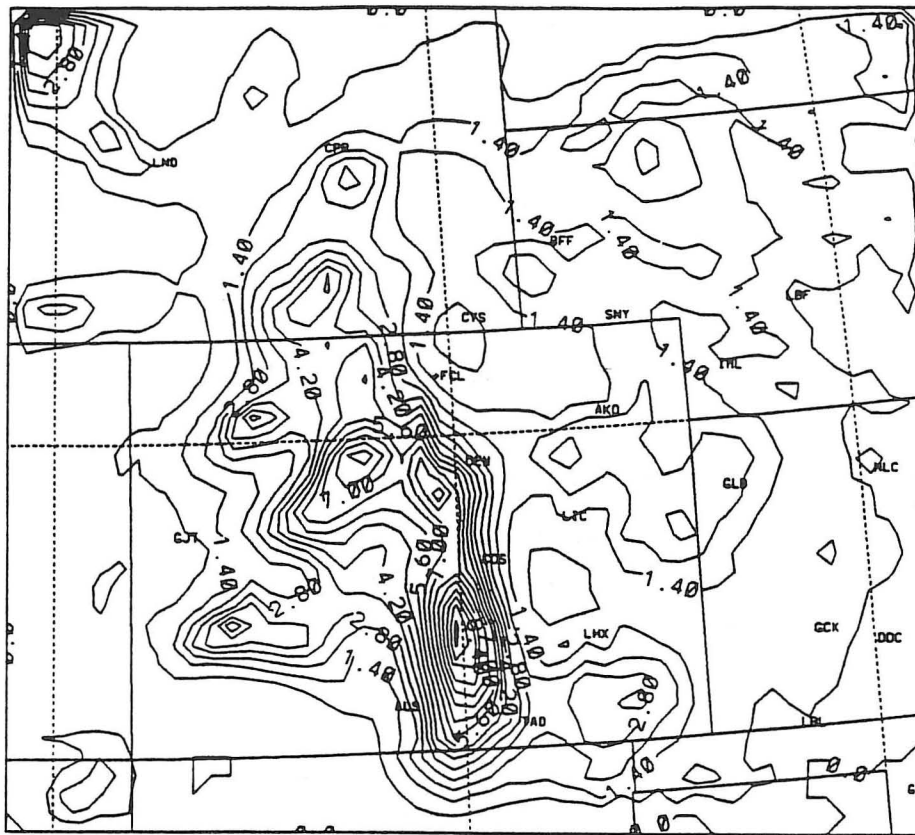
Fig. 11. Total precipitation in mm for the Colorado region for the high resolution simulations. (contours 1 mm).

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