REGIONAL-SCALE SIMULATIONS OF THE WESTERN U.S. CLIMATE

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1. INTRODUCTION

Over the past two decades the meteorological community has witnessed the evolution of general circulation models (GCMs) from studies attempting to simulate realistic large-scale dynamical regimes and energy transports to present investigations examining future climate change scenarios. This evolution is certain to continue over the next decade, as demands are placed upon the GCM community to generate realistic scenarios for future climate change on regional as well as global scales. However, fine-scale regional climate and climate variability can not be properly simulated with present coarse resolution GCMs. Even observations of regional climatology are poorly represented with the existing widely scattered rawinsonde network and relatively coarse-scale global analyses. For example, the National Meteorological Center's (NMCs) global analysis is tabulated on a 2.5° by 2.5° grid after conversion from a spherical harmonics data set truncated at wavenumber 30. In the mountainous western U.S., where climate scales are strongly coupled to the underlying topography, this 2.5° by 2.5° grid is clearly inadequate.

One approach to dealing with this regional climatology question has been to use existing coarse-scale GCM output to provide the large-scale background climate for specific regions (Rind 1988; Gutowski et al. 1991). Another alternative is to locate a regional model with a finer resolution mesh over the region of interest within the GCM. For example, a limited area model could be forced on the boundaries by the large-scale GCM output over an extended period. The feasibility of this approach has recently been demonstrated by Dickinson et al. (1989), Anthes et al. (1989), Giorgi (1989), and Giorgi and Bates (1989), using the Penn State/NCAR mesoscale model. The most encouraging aspect of these studies is that we now know that mesoscale models can provide a sufficiently detailed regional climatology.

From these pioneering studies, we were inspired to begin to develop regional climatologies with the Colorado State University Regional Atmospheric Modeling System (CSU-RAMS). Our major goal is to develop a better understanding of the hydrologic cycle in the mountainous, arid west. An advantage of using the RAMS code is that we can generate detailed descriptions of precipitation processes, which will hopefully translate into realistic surface yields of both rain and snow. In the ensuing sections, we first describe the model and its microphysics parameterizations, then continue with our methodology for incorporating large-scale data into the model grid. Preliminary results demonstrating the mesoscale variation of precipitation over the mountainous western U.S. are then presented.

2. THE MESOSCALE MODEL

The RAMS mesoscale model is a highly flexible modeling system, capable of simulating a wide variety of mesoscale phenomena. The basic model structure is described in Tripoli and Cotton (1982). More recent model developments are described in Tremback et al. (1986) and Cotton et al. (1988). The model framework for the present study incorporates a three-dimensional, terrain-following non-hydrostatic version of the code. The simulation includes topography derived from a 5-minute global data set with a silhouette averaging scheme that preserves realistic topography heights. This height data is then interpolated to the model grid which has 0.5° horizontal resolution at the tangent point of the polar stereographic grid at 40.0°N and 112.5°W. In these experiments, we cover the geographical domain from 127.5°W to 97.5°W and 27.5°N to 52.5°N. In the vertical we use 21 levels, corresponding to a resolution of 300 meters near the surface and 1000 meters at the top of the model. Non-hydrostatic equations are used so that nested grids capable of resolving cloud-scale phenomena can eventually be implemented.

At the surface, temperature and moisture fluxes are determined from the surface energy balance, which includes both short- and longwave fluxes (Chen and Cotton 1983), latent and sensible fluxes, and sub-surface heat conduction from a soil temperature model (Tremback and Kessler 1985). A modified Kuo-type cumulus parameterization is incorporated in the model, although in the present January simulation cumulus precipitation is much less important than stratiform precipitation, which is treated with a bulk microphysical parameterization. The microphysics parameterization, outlined in detail in Flatau et al. (1989), describes the physical processes leading to the formation and growth of precipitation particles within a cloud. The cloud particles can be liquid or ice, or some combination, and may have a regular or irregular shape. The scheme categorizes these particles as cloud droplets, rain drops, ice crystals, snow crystals, aggregates of ice crystals, and graupel or hail. Each species can grow independently from vapor and self-collection, or interact with other species through collision and coalescence processes. In the configuration used for this study, the mixing ratio of each species is predicted and the total concentration is diagnosed, using a specified size distribution. It is intended that the rain and snow fields will eventually be coupled to a detailed surface hydrology model.

3. DEVELOPMENT OF A REGIONAL CLIMATOLOGY

For these preliminary experiments, we are concentrating on the period 1-31 Jan 1988. We use only NMCs 2.5° by 2.5° twice daily global analyses to drive the regional model. The analyses consist of winds, temperatures, and geopotential heights at 11 standard pressure levels and relative humidity for 6 levels at and below 30 kPa. Virtual temperature and surface pressure are also available. From this global analysis, a region of the data is acquired which is large enough to totally encompass the eventual model domain by 12.5° on all sides. An example of the NMC data obtained for our simulations is given in Fig. 1 for 0000Z 5 Jan 1988. The wind vectors (Fig. 1a) give some idea of the relative coarseness of the data set, which is still of much higher resolution than most GCMs. The 50 kPa height field (Fig. 1b) reveals the presence of two deep lows at this time, one centered in the North Pacific and the other just south of Hudson Bay. Between these vortices lies a narrow high amplitude ridge over western North America.

The next stage of the data assimilation process involves the preparation of a gridded isentropic vertical coordinate data set, obtained by vertically interpolating the NMC vertical pressure coordinate data set to specified isentropic levels, and then horizontally interpolating this data onto a higher resolution 0.6° grid. The use of an isentropic vertical coordinate has some advantages, namely, that synoptic flow is adiabatic to a first-order approximation, and hence, this analysis should give a realistic estimate of the flow between the NMC data points. The disadvantages of isentropic coordinates, such as having isentropes which intersect the ground, is not a factor in this analysis. The isentropic analysis is performed over a smaller area than the previous pressure stage, to avoid potential boundary problems, but is still 5° larger on all sides than the model grid. In the vertical, 30 isentropes are specified to increase the data resolution, particularly near the surface. A plan view of the isentropic stage pressure data for the 320°K isentrope is given in Fig. 2. Steeply sloping isentropes near 40°N signify the location of the polar front. These sloping isentropes, as well as the mixing ratio, are depicted in a north-south cross-section in Fig. 3. This figure shows that very dry conditions exist near the surface north of 34°N, which is over the Great Basin, while moister conditions are present south of that latitude, and in a broad tongue between 70 and 90 kPa.

With the isentropic data set, we can now initialize the RAMS model. This is done by interpolating the isentropic data onto the model grid (0.5° resolution), to obtain a full set of prognostic fields for model integration. The model domain, along with the topography used, is shown in Fig. 4. The topography is smoothed to only contain wavelengths greater than or equal to 4 times the horizontal resolution, so as not to introduce unresolvable modes into the simulation. Lateral boundary conditions of the domain are updated each time-step by linearly interpolating between successive 12-hour large-scale analyses.

We compare two diverse methods for generating the regional climatology applicable to January 1988. In the first method the model is initialized from the NMC analysis and then integrated for 12 hours. These simulations are re-initialized every 12 hours, but this could be extended to longer periods if further analysis indicates that this technique does not allow the model to fully develop a realistic mesoscale circulation within this time frame. We will present comparisons for the average of sixty-two 12-hour simulations at 3,6,9,12 hours to address this question. The second method initializes only the first 12-hour simulation and then updates the lateral boundary conditions toward each successive 12-hour analysis, throughout the rest of the month. This methodology is similar to that adopted by Giorgi and Bates (1989). We are currently investigating methods of slightly nudging interior model grid points as well, to keep the mesoscale simulation more closely adjusted to the large-scale conditions for the month-long run.

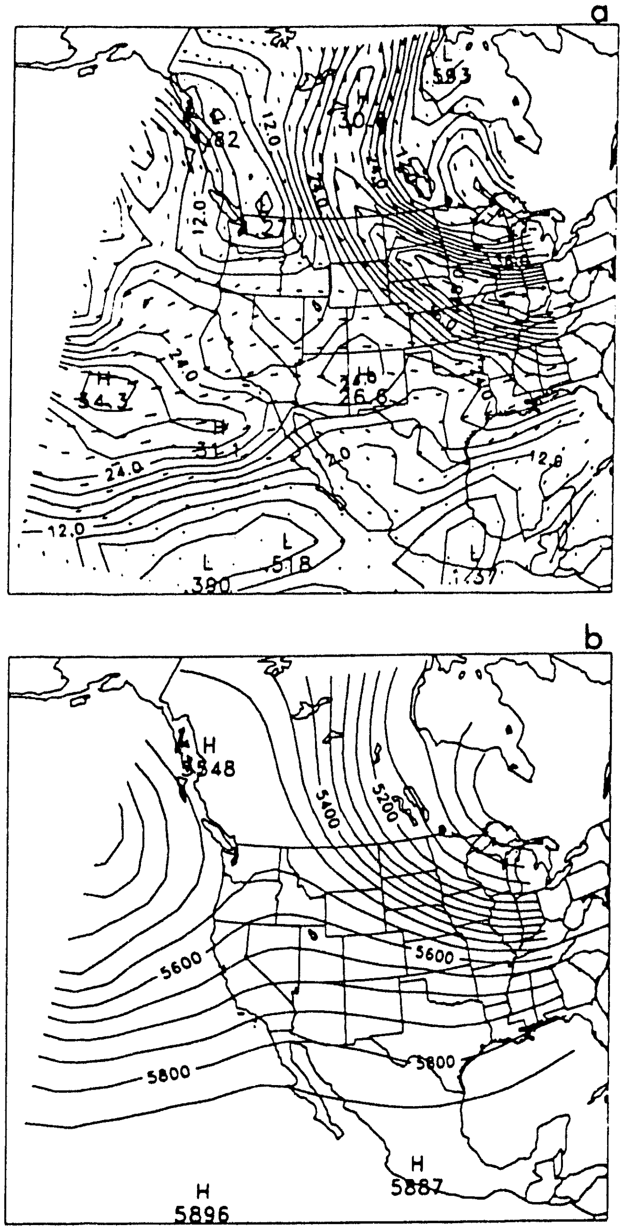

Fig. 1. NMC 2.5° data at 50 kPa over a portion of northwestern hemisphere at 0000Z 5 Jan 1988 for (a) wind speed every 3.0 ms^{-1}, and (b) geopotential heights every 50 m.

Preliminary analyses have shown that after an initial spin-up time, the re-initialized climatology begins to resemble the month-long climatology run in many aspects; the advantage of the first method is that many individual 12-hour runs can be done simultaneously (i.e. in parallel), while the second method requires sequential job submission, greatly increasing the real-time cost of the experiment.

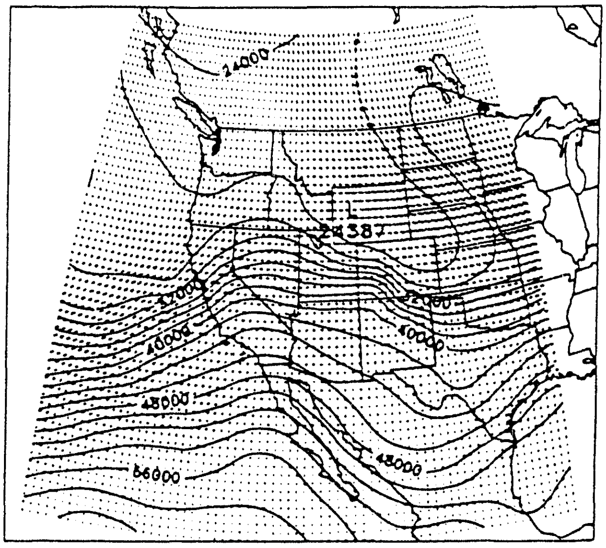

Fig. 2. Wind vectors and pressure (Pa) on the 320°K surface at 0000Z 5 Jan 1988.

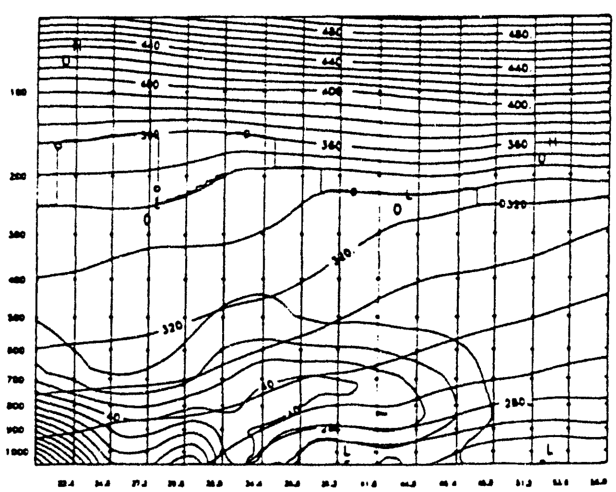

Fig. 3. South to north cross-section at 117.0°W of potential temperature θ (in $°K$) and mixing ratio r_v (in g/kg x 10^1) for 0000Z 5 Jan 1988.

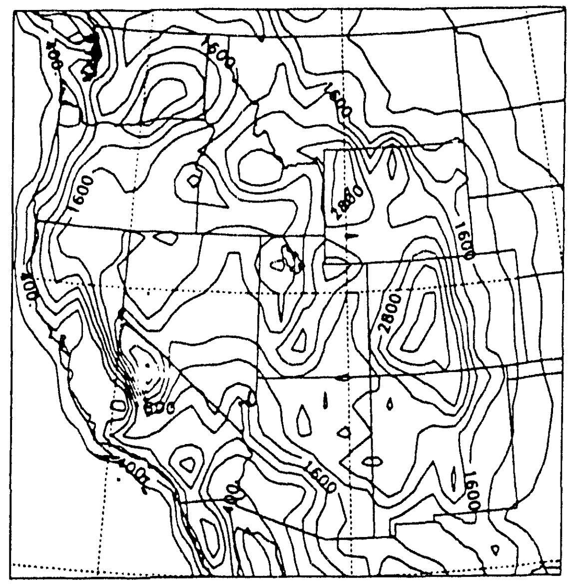

Fig. 4. Model domain over the western U.S. and topography heights in meters. Contour interval 300 m.

4. PRELIMINARY RESULTS

In this section, we show several fields from two 12-hour simulations to demonstrate how the model is capable of capturing essential mesoscale weather features over the western U.S., the ensemble of which constitutes the regional climate. In Fig. 5 the accumulated precipitation fields over the model domain for the 12 hours ending at 0000Z 5 Jan 1988 are shown. The large-scale flow at this time was shown in Figs. 1-3. The figure shows that up to 5 mm of rain has accumulated over parts of the Sacramento Valley in California (Fig. 5a), with lesser amounts over the lower elevations of the Great Basin. Snowfall is widespread over a large portion of the intermountain west (Fig. 5b), with a maximum of 5.7 mm (water equivalent) over northeastern Nevada. Note the well-defined rain/snow line over the northern Sierra Nevada in California at about 1600 msl. Snow amounts decrease significantly in the lee of the Sierra Nevada and other major ranges, due to mountain wave effects which produce strong subsidence in these areas.

Over the following 24 hours, the system responsible for the precipitation in Fig. 5 progressed onshore and southward. This is reflected in the accumulated rain and snow from the 12-hour simulation ending at 0000Z 6 Jan 1988 (Fig. 6). Rainfall during this period (Fig. 6a) is concentrated in the Central Valley and Sierra Nevada foothills in California, with lesser amounts over northern Arizona. Accumulated snowfall totals of up to 9 mm occur over the central Sierra Nevada (Fig. 6b), with a belt of snow stretching eastward into the Colorado Rockies. The areal coverage of the precipitation in both of these simulations compares favorably with published observations. However, these are only preliminary comparisons, and more rigorous comparisons are necessary and forthcoming.

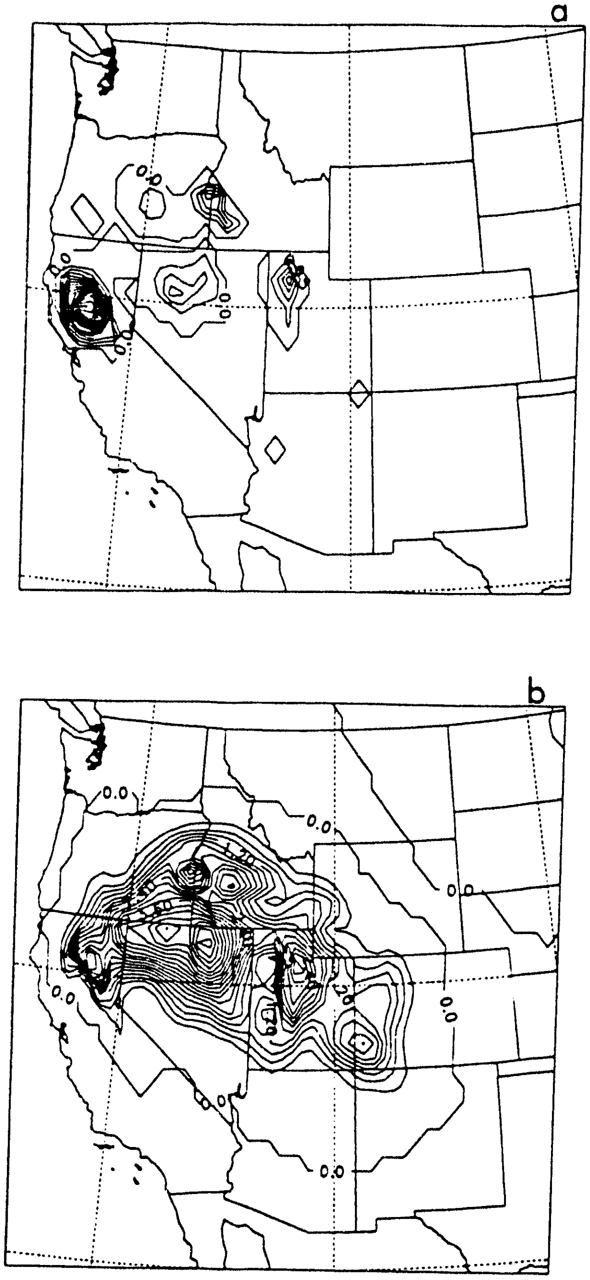

Fig. 5. Accumulated (a) rain, and (b) snow in mm at 0000Z 5 Jan 1988. Contour interval 0.3 mm.

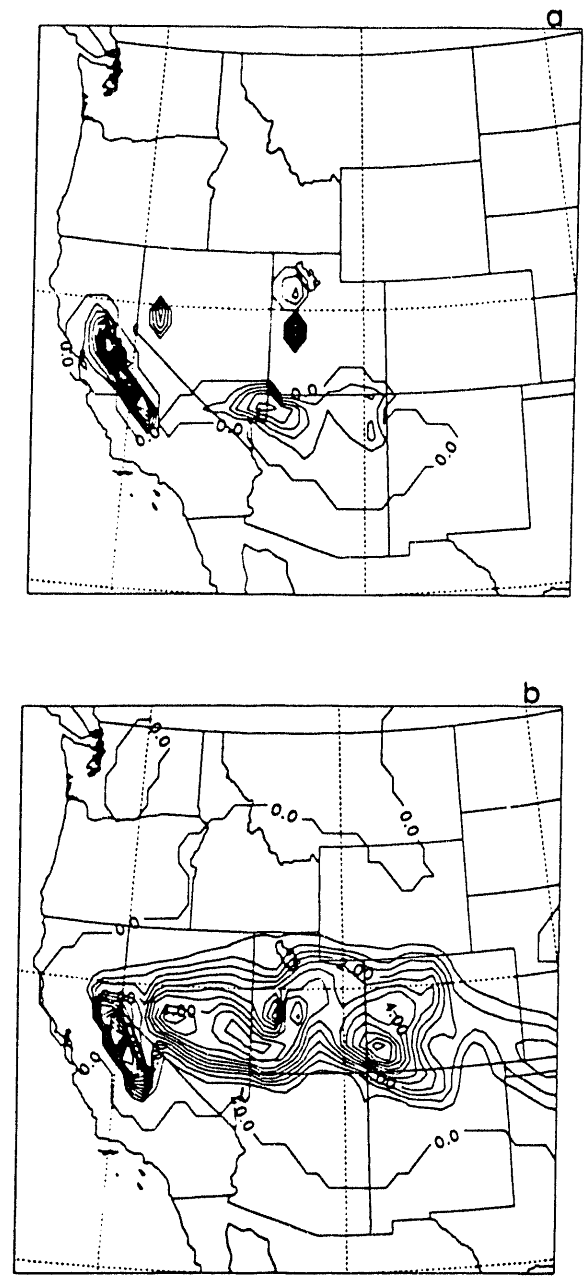

Fig. 6. As in Fig. 4, but for 0000Z 6 Jan 1988, and contour interval of 0.5 mm in (b).

5. SUMMARY

Preliminary results from our regional climatology study for January 1988 are encouraging. The dependence of precipitation on topography over the complex terrain of the model domain is clearly demonstrated, as is the ability of the microphysics parameterization to produce realistic liquid and ice phase precipitation fields and accumulations. However, further judgments on the capabilities of the model await additional analysis for the entire month-long January climatology. Averages of the precipitation and other relevant fields will be presented at the conference. Ultimately, we plan to extend our study to include the grid nesting capabilities of the RAMS model and generate even higher resolution climatologies for various western U.S. river-basins, while still maintaining our 0.5° grid for assimilating large-scale data. Work is currently in progress to assimilate data from the Los Alamos GCM (Kao et al. 1990) to provide the boundary forcing for the RAMS model. We are also planning a regional climatology study of summertime wind and precipitation patterns with RAMS. This season appears to be intrinsically more difficult to simulate, due to the very localized nature of convective storm development.

7. REFERENCES

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