Development of a Regional-Scale Climate Model With a Detailed Microphysics Parameterization

J. E. Bossert
C.-Y. J. Kao
J. L. Winterkamp
Earth and Environmental Sciences Division
Los Alamos National Laboratory
Los Alamos, NM 87545

J. O. Roads
S.-C. Chen
Scripps Institution of Oceanography
University of California at San Diego
La Jolla, CA 92093

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, since the GCM community, through the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) and Computer Hardware, Advanced Mathematics and Model Physics (CHAMMP) programs, has been challenged with producing realistic scenarios for future climate change down to regional-scales (~50 km). Unfortunately, the development of high-resolution GCMs is at least 5 to 10 years away, while the need for information on potential climate change impacts over specific regions is immediate.

The regional climate issue can be dealt with in several ways. One approach has been to use existing coarse-scale GCM output to focus in on particular regions (Gutowski et al. 1991; Grotch and MacCracken 1991). However, the mismatch in scale between the GCM and the processes driving the regional climate limit the representativeness of these studies. A more realistic alternative is to implement a model with a finer resolution mesh over the region of interest within a GCM. For example, a limited area (i.e., mesoscale) model could be initialized with, and forced on the boundaries by, GCM output or other large-scale data sets, over an extended period. The feasibility of this nesting approach has recently been demonstrated using either large-scale global analyses (e.g., ECMWF or NMC) or GCM output by Dickinson et al. (1989), Giorgi and Bates (1989), Giorgi (1990) using the Penn State/NCAR mesoscale model, and Bossert et al. (1992) using the Colorado State University Regional Atmospheric Modeling System (CSU-RAMS). These studies have shown that mesoscale models can provide a regional climatology that is of sufficient detail to be useful for global change assessments, provided that the model's performance can be adequately validated with existing data.

The research described herein is an extension of Bossert et al. (1992), which described the methodology used for ingesting large-scale data (NMC) into a mesoscale model, along with preliminary results from a regional climate simulation of the mountainous western U.S. In this paper, we focus upon a comparison between observed data and the model-generated surface fields for a month-long simulation of January 1988 over the same western U.S. domain. If the model can be validated against available observations over several of these month-long simulations during different seasons, we would be confident in its ability to realistically simulate regional-scale climate change variations using GCM output. Of course, the usefulness of such a simulation would depend upon the credibility of the GCM output used to drive the regional model.

A potential advantage of using the RAMS code for regional climate simulations is the sophisticated microphysics parameterization which provides a physically based description of cloud formation and precipitation processes. These month-long simulations also provide us with several opportunities for incorporating ARM data into the research. Initially, we will examine the performance of the cloud microphysics parameterization with the extended ARM observations. We also plan to initialize the dynamical and microphysical fields in RAMS by assimilating ARM observations into the model. Through the RAMS model's grid nesting capabilities, we can also provide dynamically consistent model-generated output as input to the single-column GCM testbed. Thus, our foremost goal is not only to better describe the cloud processes affecting the regional climate, but also to materialize the concept of "hierarchical diagnosis" under the ARM program.

In the ensuing sections, we briefly describe the model configuration used, our regional climate modeling strategy, and then describe our preliminary simulations. In particular, we examine the ability of the RAMS model to simulate the observed climate over the complex terrain of the western U.S. for January 1988.

The Mesoscale Model

The RAMS model is described in these Proceedings in Kao and Bossert (1992), and thus, only a brief description of the particular model configuration used will be given here. The model framework for the present study incorporates a three-dimensional, terrain-following hydrostatic version of the code. The simulation includes topography derived from a 10-minute global data set with a silhouette averaging scheme that preserves realistic topography heights. These height data are 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.

The model includes a realistic treatment of surface processes, which includes both short- and longwave fluxes, latent and sensible fluxes, and sub-surface heat conduction from a soil temperature model (Tremback and Kessler 1985). The microphysics parameterization (Flatau et al. 1989), describes the physical processes leading to the formation and growth of precipitation particles within a cloud. 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.

Simulation Development

For the experiments described herein, we use two separate methodologies to simulate the period of 1 through 30 January 1988. The NMC 2.5° by 2.5° twice daily global analyses are used to initialize, as well as "nudge" the regional model boundaries via a Newtonian relaxation scheme. The NMC analyses consist of winds, temperatures, and geopotential heights at 11 standard pressure levels and relative humidity for 6 levels at, and below, 30 kPa. An isentropic analysis vertically interpolates these vertical pressure coordinate data onto specified isentropic levels, and then horizontally interpolates these data onto a higher resolution 0.6° grid.

The model is initialized from the isentropic data set, by interpolating the isentropic data onto the model's terrain following σ_z 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 Figure 1. The

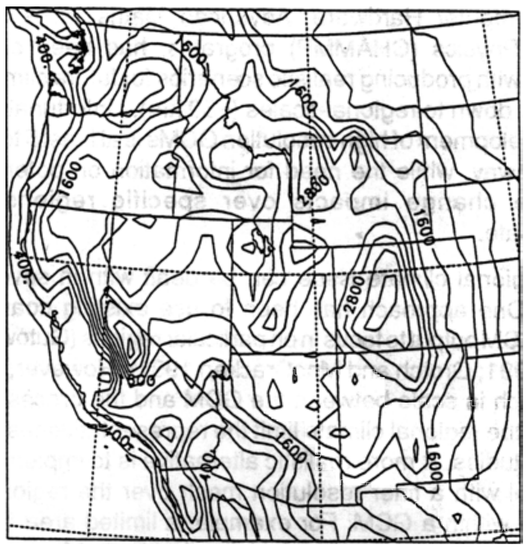

Figure 1. Model domain over the western U.S. and topography heights in meters. Contour interval 300 m.

topography is smoothed to contain only wavelengths greater than or equal to 4 times the horizontal resolution, so as not to introduce unresolvable modes into the simulations.

We compare two diverse methods for generating the regional climatology for January 1988. In the first, the model is initialized from the NMC analysis and then integrated for 12 hours with boundary nudging toward the following NMC analysis over the first 5 lateral grid points. These lateral boundary conditions are updated each timestep by linearly interpolating between the successive 12-hour NMC analyses. After 12 hours of integration, the simulation is re-initialized with the following 12-hour analysis; and the cycle repeats through the 30-day simulation. This re-initialization technique can be thought of as a crude form of data assimilation, but is rather drastic since it eliminates all previous mesoscale information and cloud/precipitation development every 12 hours. In the second method, the model is initialized at the start of the 30-day run, with the lateral boundaries nudged toward each successive 12-hour analysis, throughout the entire month-long integration. This methodology is similar to that adopted by Giorgi and Bates (1989). However, we have chosen, in this simulation, to weakly nudge over 15 boundary points, in order to keep the mesoscale simulation more closely adjusted to large-scale conditions, and to provide a smooth transition between the boundary and interior points. We compare the results from both of these month-long simulations with available observations to demonstrate the climatology that results from these different simulation strategies.

Results

In this section, we compare the monthly averaged surface precipitation and temperature fields from both the re-initialized and continuous RAMS climatology simulations with observed conditions for January 1988, as determined from the National Climate Data Center's cooperative station network. This network includes over 300 quality checked stations of long-term record within the western U.S. The station locations used in this analysis are shown in Figure 2, along with the NMC analysis grid points and the RAMS model grid points. We are currently acquiring additional data sets including rawinsondes, first-order stations, and satellite data to provide a more extensive observational database for model validation.

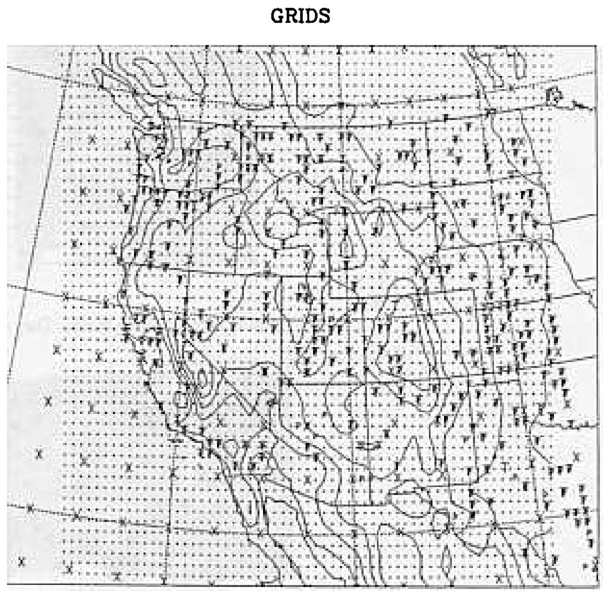

Figure 2. NCDC cooperative station locations, where "T" and/or "P" indicates whether temperature and/or precipitation are recorded. Also shown are NMC 2.5° by 2.5° analysis grid points (x's), and model grid points (dots). Topography contours from 0 to 3000 m by 500 m.

As previously mentioned, precipitation in the model simulation is produced by the microphysics parameterization, which calculates the mixing ratios of five different species. Figure 3 shows an example of the output from this package for January 5 and 6, 1988, from the continuous run at 0000 UTC. The simulated mid-tropospheric flow field at 0000 UTC January 5, 1988, (Figure 3a) shows that a progressive trough has moved into the western U.S., with its axis located over Nevada. Figures 3b and 3c illustrate the three-dimensional rain and snow mixing ratio fields for 0000 UTC January 5, 1988, and 0000 UTC January 6, 1988, respectively. The vertical scale is greatly exaggerated in this perspective to show the rain in the lower elevations and below the freezing level, while the snow exists through a greater vertical depth, and over a more extensive region, especially over the Great Basin and central Rocky Mountains. The movement of the precipitation over the 24-hour period is linked to the southeastward progression of the short-wave inducing the precipitation development. The total cloud extent at 0000 UTC

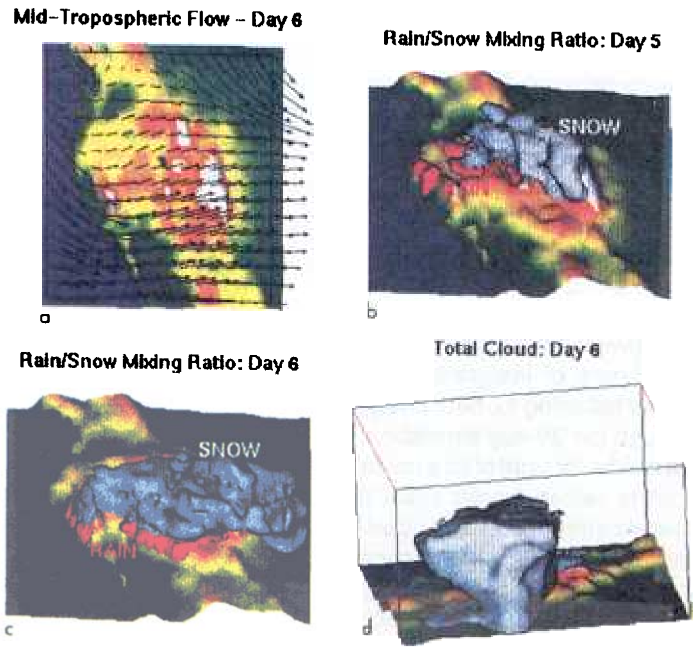

Figure 3(a). Simulated mid-tropospheric winds over the model domain topography at 0000 UTC January 6, 1988. (b) 3-D perspective of resolved topography, and model-generated rain (red) and snow (white) for 0000 UTC January 5, 1988. (c) As in (b) but for 0000 UTC January 6, 1988. (d) 3-D perspective looking west at total cloud amount at 0000 UTC January 6, 1988. Note: vertical dimension is greatly exaggerated for clarity in (b), (c), and (d).

January 6, 1988, is shown in Figure 3d, from a perspective looking westward from the Mississippi River. The figure shows the horizontal extent of the upper tropospheric shield of ice cloud, which covers much of the southwestern U.S. A sharp boundary to the cloud is noted north of 42°N, due to the dry, subsident northwesterly flow from Canada, evident in Figure 3a. These figures demonstrate that the microphysics parameterization can produce a fairly realistic representation of cloud and precipitation processes for a given atmospheric flow pattern.

The precipitation that developed over the course of the month is shown in a time-series of the precipitation rate for each day of the month in Figure 4. This time-series is determined by taking the daily accumulated value from the cooperative stations and the model grid point nearest to each data station. The simulated precipitation rate for both the re-initialized and continuous runs are obtained by subtracting the 11th and 23rd hour accumulated precipitation values from the 12th and 24th hour values every 12 hours, and then averaging the two values each day to get the daily rate.

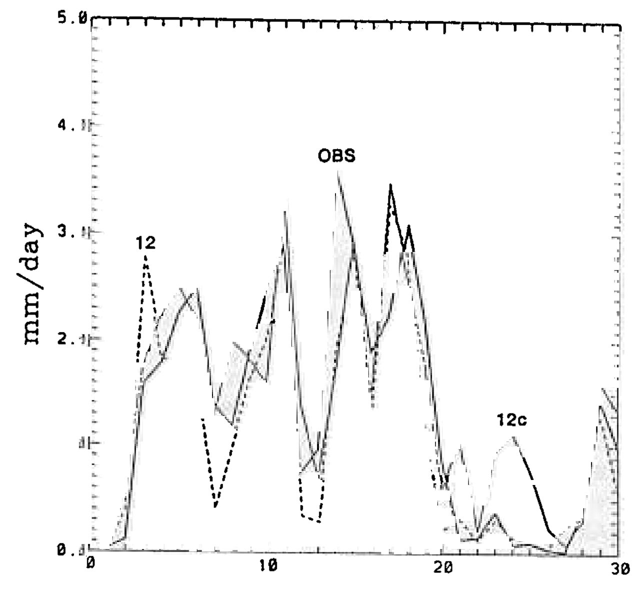

Figure 4. Time-series of precipitation rate (mm/day) for January 1988, from station data (heavy solid, labeled "OBS"), continuous simulation (light solid, labeled "12c"), and re-initialized simulation (dashed, labeled "12").

Both simulations do a reasonable job of capturing the averaged precipitation over the western U.S. Clearly, the detailed microphysics scheme is capable of providing a realistic estimate of the actual precipitation in an average sense.

Spatial variations are shown in Figure 5, for observed and simulated precipitation rates. The observed precipitation (Figure 5a) which has been interpolated onto the model grid, reveals that the highest monthly precipitation rates (up to 11.41 mm/day) during January 1988 are in the northwestern U.S. along the coastal margin and in the Cascade Range. Other relative maxima occur over the northern Sierra Nevada Range and in the high mountain areas of Colorado and Wyoming. The re-initialized run (Figure 5b) also shows substantial precipitation within the northwest, however, the maximum has shifted inland over the high topography, a trend also evident in the other

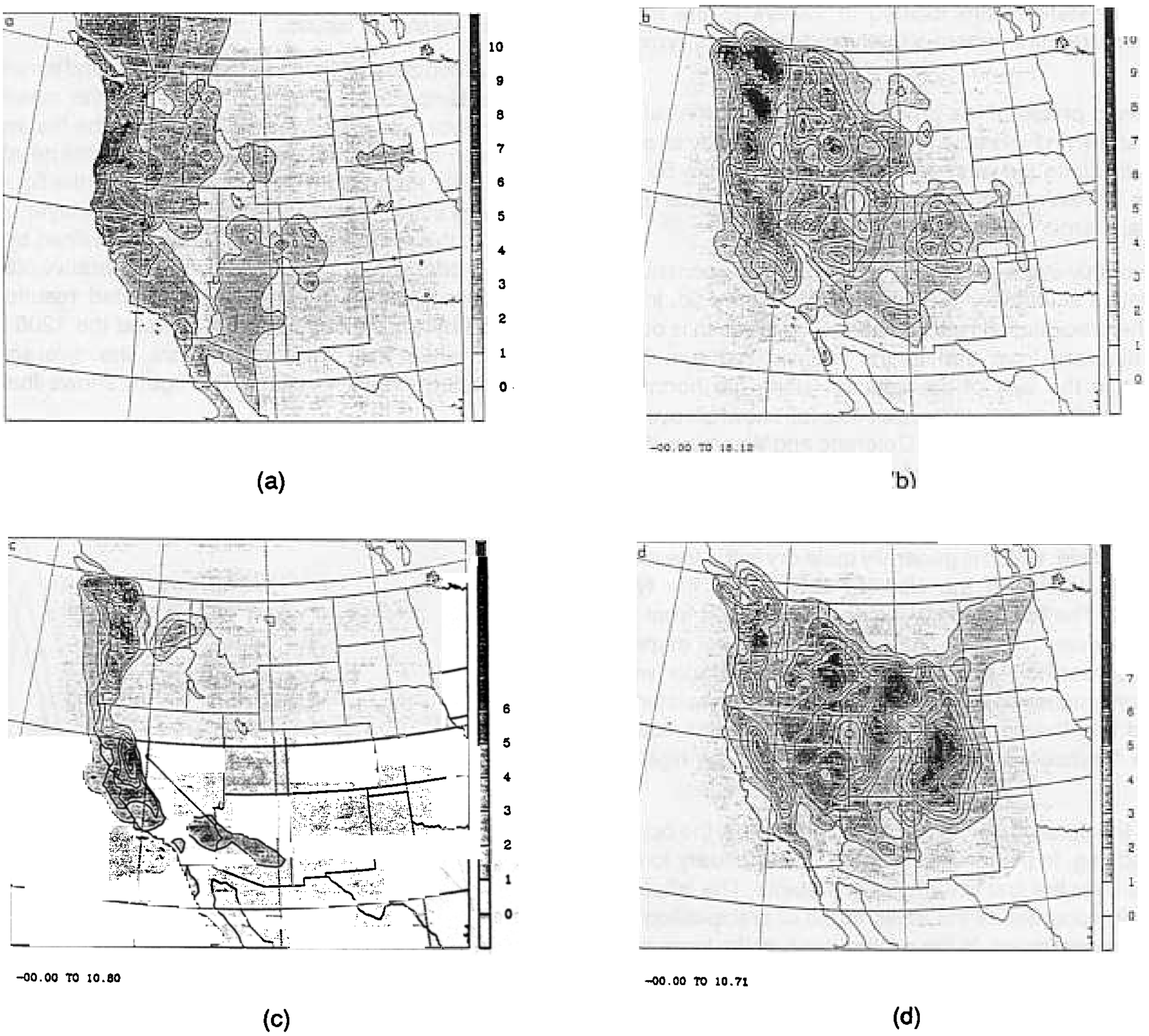

Figure 5. (a) Observed total precipitation (mm/day) from station data, interpolated to model grid. (b) Simulated total precipitation (mm/day) from the re-initialized simulation. (c) As in (b), but for rainfall only. (d) As in (b), but for the continuous simulation.

relative maxima, which show an increase of precipitation with altitude.

While somewhat different in magnitude than the observed rates, this result is encouraging, since precipitation increases with altitude in winter, primarily due to orographic lifting and condensation of the impinging airmass. This result also points out a shortcoming in the cooperative station data. Since none of the more than 300 stations are located above 2750 m (9000 ft), these observations are biased toward lower elevation stations. Many of the lower elevation stations are located in valleys in the lee of mountain ranges, where winter precipitation is typically low.

The liquid phase of the precipitation for the re-initialized run is shown in Figure 5c, which shows that nearly all of the rain falls along the west coast. Comparing Figure 5b with Figure 5c reveals that most of the precipitation east of the coastal margin falls as snow.

The monthly averaged precipitation rate for the continuous simulation of January 1988 is shown in Figure 5d. In this run, the precipitation rate and spatial distribution is decidedly different from that in the re-initialized run. Most notable is the lack of precipitation along the northwest coast, and the greatly increased rate (all snowfall) over the central Rocky Mountains in Colorado and Wyoming. While this difference is the topic of current investigation with the microphysics parameterization, there are several possible reasons for the difference. One major point involves the moisture field, which is generally quite dry in the low levels over the interior of the western U.S. within the NMC analysis. The simulation, which is re-initialized from this analysis every 12 hours, reflects this low level dryness, thus decreasing the precipitation over the interior west. The continuous run, on the other hand, allows moisture to advect into the domain interior over longer time scales, where it subsequently precipitates out over the high terrain.

Along the coast, the differences may be due to the boundary nudging. In the re-initialized run, the boundary forcing occurs over the first five model grid points. The influence of this is apparent as the sharp cutoff of precipitation just off of the west coast. In the continuous run, the large scale influence extends over the first 15 lateral grid points, but the coefficient controlling this influence is increasingly reduced as the interior of the domain is approached, so as to be insignificant by the 15th grid point. However, along the west coast the impact of the boundary nudging may still be enough to suppress the horizontal convergence necessary to drive the microphysics parameterization. Still another reason that both simulations tend to develop more precipitation over the high terrain of the Cascades than along the coast, as was observed, is the grid resolution, which is too coarse to resolve the Coastal Range. Instead, a long slope exists inland from the coast, which culminates at the crest of the Cascades. Lifting associated with this long, continuous slope tends to produce the simulated inland precipitation maximum. Ongoing and future research is aimed at addressing these boundary forcing and grid resolution issues.

The final comparison involves the observed and simulated surface temperature (Figure 6). Actually, the simulated temperature field is an average value over the first model layer, and hence is indicative of the temperature at approximately 150 m agl. The line labeled "0" in the figure, is the model initial state temperature in the first layer. As in Figure 4, this temperature time-series is obtained by taking the model grid point nearest to the cooperative station. In addition, the initial state and simulated results are obtained by averaging the 0000 UTC and the 1200 UTC values, while the observations are the average of the reported max/min values. The figure shows that the

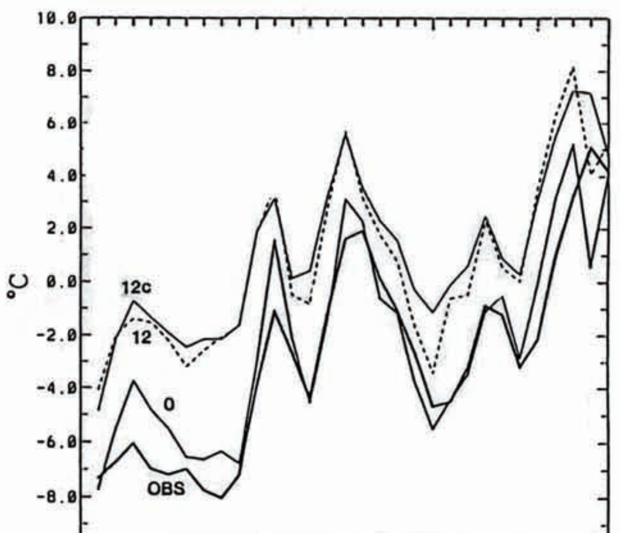

Figure 6. Time-series of average daily temperature (°C) for January 1988, from surface station data (labeled "OBS"), NMC surface data (labeled "0"), and the re-initialized (labeled "12") and continuous run (labeled "12c") at 144 m.

day-to-day surface temperature variability in the model is well correlated between the two simulations and the observations. This result shows that the model is capable of capturing the observed temperature climatology in the most basic, large-scale sense. Of further interest is the systematic "warm bias" that both simulations show when compared with the initial state temperature, which closely follows the observed cooperative station data. A closer look at the re-initialized run has shown that this warm bias appears very quickly in the simulation, after only 1-hour of integration time. We are currently investigating the nature of this problem.

Of interest is the fact that both simulation methodologies, while very different, produce very similar near-surface temperatures. This result leads to several observations regarding the development of climatologies from regional models. It appears that the re-initialized run, while being a very drastic form of data assimilation, shows nearly the same skill (in the large-scale averaged sense) as the continuous run, in which the mesoscale model has much more freedom to determine the regional climate. Perhaps this result also points to our method of slightly nudging well into the simulation domain in the continuous run. While very weak in the interior, this forcing may still be enough to overwhelm much of the mesoscale signal. More testing will be necessary to determine the optimal amount of large-scale influence to include in the simulation.

Summary

Results from our regional climatology study for January 1988 are encouraging in several ways. The ability of the mesoscale model to capture the average precipitation and temperature over the western U.S. was clearly demonstrated using an independent data set for comparison. The dependence of precipitation on topography over the complex terrain of the model domain was also simulated, as was the ability of the microphysics parameterization to produce fairly realistic spatial patterns of liquid and ice phase precipitation accumulations. The re-initialized and continuous simulations both showed similar degrees of skill in reproducing the observed fields, casting some question as to what is an acceptable method of performing regional climate simulations. More experimentation will be necessary to resolve this issue. Ideally, we would like to incorporate a more sophisticated data assimilation scheme into the model.

The two separate month-long simulations have elucidated many deficiencies in our set-up of the simulation, as well as several potential weaknesses within the model parameterizations. These weaknesses might not have been apparent in a short-term integration of the model (~24 hours), which to date has been the primary way in which mesoscale models have been used. These climatology simulations provide a testbed in which we can investigate the robustness of parameterization schemes for grid resolutions at which they may be used in future climate models. In addition, while a substantial amount of testing and validation is still required, this study and others like it have shown that regional models can provide realistic climatological information at scales which are unresolved in present GCMs.

Concluding Remarks

In this study, we have focused mainly upon the large-scale averaged features in our comparisons, however, in future work we intend to focus upon the mesoscale variability inherent within the simulation, since it is at these scales (meso-β/meso-α) at which climate change will most heavily impact human activities, and at which we presently have the poorest understanding of the climatology. This is especially true within regions of complex terrain. 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). These data will provide the boundary forcing for the RAMS model to examine in more detail impacts upon the western U.S. of cold/dry and warm/wet anomalous wintertime wave patterns from a 10-year GCM simulation. We are also planning a regional climatology study of July 1987. Through this study, we will investigate the performance of several convective parameterizations and also examine, through grid nesting, the evolution of convective storms over the Oklahoma area as a preliminary testbed for future, intensive studies of the ARM Cloud and Radiation Testbed (CART) site and surrounding environs.

References

Bossert, J. E., J. O. Roads, C.-Y. J. Kao, S.-C. Chen, and K. Ueyoshi. 1992. Regional-scale simulations of the western U.S. climate. Preprints, Third Symposium on Global Change Studies, Atlanta. *Amer. Meteor. Soc.* 24-28.

Dickinson, R. E., R. M. Errico, F. Giorgi, and G. T. Bates. 1989. A regional climate model for the western U.S. *Clim. Change* 15:383-422.

Flatau, P. J., G. J. Tripoli, J. Verlinde, and W. R. Cotton. 1989. The CSU-RAMS Cloud Microphysics Module: General theory and code documentation. Atmospheric Science Paper No. 451, Colorado State University, Dept. of Atmospheric Science, Fort Collins, Colorado.

Giorgi, F. 1990. On the simulation of regional climate using a limited area model nested in a general circulation model. *J. Climate* 3:941-963.

Giorgi, F., and G. T. Bates. 1989. The climatological skill of a regional model over complex terrain. *Mon. Wea. Rev.* 117:2325-2347.

Grotch, S. L., and M. C. MacCracken. 1991. The use of general circulation models to predict regional climate change. *J. Climate* 4:286-303.

Gutowski, W. J., D. S. Gutzler, and W.-C. Wang. 1991. Surface energy balances of three general circulation models: Implications for simulating regional climate change. *J. Climate* 4:121-134.

Kao, C.-Y. J., G. A. Glatzmaier, and R. C. Malone. 1990. Global three-dimensional simulations of ozone depletion under postwar conditions. *J. Geophys. Res.* 95:22495-22512.

Kao, C.-Y. J., and J. E. Bossert. 1992. Numerical simulations of an idealized convective system: Comparisons between parameterized and explicitly resolved clouds. DOE ARM 1991 Science Team Proceedings.

Tremback, C. J. and R. Kessler. 1985. A surface temperature and moisture parameterization for use in mesoscale numerical models. Preprints, Seventh Conf. on Numerical Weather Prediction, Montreal. *Amer. Meteor. Soc.*