Title: A Coupled Regional Climate-Biosphere Model for Climate Studies

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The objective of this project has been to develop and test a regional climate modeling system that couples a limited-area atmospheric code to a biosphere scheme that properly represents surface processes. The development phase has included investigations of the impact of variations in surface forcing parameters, meteorological input data resolution, and model grid resolution. The testing phase has included a multi-year simulation of the summer climate over the Southwest United States at higher resolution than previous studies. Averaged results from a nine summer month simulation demonstrate the capability of the regional climate model to produce a representative climatology of the Southwest. The results also show the importance of strong summertime thermal forcing of the surface in defining this climatology. These simulations allow us to observe the climate at much higher temporal and spatial resolutions than existing observational networks. The model also allows us to see the full three-dimensional state of the climate and thereby deduce the dominant physical processes at any particular time.

1. Background and Research Objectives

The potential impact of global climate change has fueled recent interest in understanding present and future climate at much smaller spatial scales than current general circulation models (GCMs) can deliver. A recently developed technique for investigating climate at five to ten times higher resolution than in GCMs has been to nest a mesoscale model within a GCM or other global data set for long-term integrations. This nested modeling approach to investigate regional climate was initiated by Dickinson et al. [1]. The methodology and verification of the technique has been refined over the last five years by Giorgi and colleagues using a version of

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the NCAR/PSU MM4 mesoscale model [2-4]. Another mesoscale model, the Regional Atmospheric Modeling System (RAMS) has been applied at LANL to the simulation of regional climate over the western United States [5,6]. These studies have shown that regional climate modeling can advance our understanding of climate change impacts over specific areas of the globe. These modeling results can provide crucial guidance for developing strategies to cope with climate change at more localized scales where policy is most effectively implemented.

The primary objective of this LDRD project has been to develop and test a regional climate modeling system that includes a sophisticated biosphere scheme. A secondary objective was to validate this modeling system by simulating the present-day climate over a specific region of the United States, at higher resolution than has been previously attempted in other studies. The results from such a study can provide an understanding of climate processes over regions with a dearth of observed data. It is important to understand these processes and validate the regional climate models with existing climate data bases before we can have confidence in their utility for predicting future global change scenarios. As part of this exercise, we also hope to understand more about present-day climate at sub-observational scales.

These investigations can open a whole new realm of research opportunities. Toward this end, the present study includes an investigation of regional climate over the southwestern United States. The Southwest (here defined as Arizona, Colorado, New Mexico, and Utah) is a region with highly localized climates caused by the complex terrain of the central and southern Rocky Mountains. The summer climate of the Southwest is unique in being primarily controlled by thermally-driven circulation systems at local-to regional-scales [7].

2. Importance to LANL's Science and Technology Base and National R&D Needs

This work provides a thoroughly tested regional climate modeling system to LANL's science and technology base and expands the current capabilities within the Laboratory's Global Change Program. With this modeling system, we have improved our understanding of present climate at higher resolution than any previous studies to date. Nationally, the proposed work can benefit the Department of Energy (DOE) ARM and CHAMMP programs and the multi-agency GEWEX/GCIP program by enhancing our understanding of regional climate and hydrology processes. This project can benefit a range of geoscientists, including climatologists, water resource managers, air quality specialists, and ecologists, all of whom are concerned with the variability of the climate system.
3. Scientific Approach and Results

Our general approach has been to use a coupled biosphere/atmosphere modeling system to study various aspects of regional climate. This has been accomplished by initially performing numerical simulations that demonstrate the impact of surface processes on both diurnal circulations and short-term climate statistics, with a series of sensitivity experiments over several regions of the United States. These simulations revealed the importance to both regional weather prediction and climate of realistically specifying surface processes.

After implementing an improved parameterization of surface processes, we have focused upon longer-term, regional climate simulations with the coupled atmosphere/biosphere modeling system. For the regional climate simulations, we have also obtained gridded meteorological data sets at 2.5° from the National Meteorological Center (NMC) (through our UCSD/Scripps collaborator) to initialize and nudge the model. We then performed month-long simulations over the entire United States for a winter (January 1988) and a summer month (July 1987), with and without the observed vegetation cover. These runs were performed to test in a dramatic fashion the influence of realistic vegetation effects upon the resulting month-long climate.

In the final year of the project, we completed a nine-month simulation of the regional climate over the southwestern United States and Mexico encompassing the summer months (June, July, and August) of 1989-91. The simulation uses two grids, an outer one having 80 km resolution covering the entire western US southward into central Mexico, and an inner nested grid over just the Southwestern states (Arizona, New Mexico, Utah, and Colorado) at 20 km. This grid configuration allows us to capture on the coarse grid the summertime monsoon circulation that develops over Mexico and transports moisture into the Southwest. Within the same simulation, we also resolve the individual mountain ranges over the Southwest at higher resolution to examine in detail their associated wind and precipitation systems. The results are presented as an ensemble mean of the nine summer months. The model simulations are initialized and continuously nudged with gridded data from NMC's 2.5° global analysis, and nine continuous month-long simulations are performed.

The results from this nine-month climate simulation are extensive, so here we can provide only a brief overview of the average summer diurnal circulation and associated convective precipitation that evolve over the Southwest. First, however, we need to examine the thermodynamic processes that drive these diurnal circulations. In Fig. 1a, we show the potential temperature difference field at 1700 m above ground level (agl) between day [1700 Local Standard Time (LST)] and night (0500 LST) over the entire domain of the outer (80 km) model grid. The figure shows that temperature increases through a deep layer due to strong
daytime heating of the land surface. This diurnal temperature perturbation is relatively minor at sea level, but becomes increasingly strong over the higher terrain of the intermountain west and the Sierra Madre of Mexico. The wind response to this thermally-induced oscillation is a large-scale diurnal "plateau" circulation system, first defined by Reiter and Tang [7] using the relatively few rawinsonde soundings that are available. Near the surface this wind system includes a well-defined convergent flow into the plateau by day caused by the pressure decrease shown in Fig. 1a, and a corresponding divergent flow off of the plateau at night, due to cooling of the elevated terrain.

This circulation pattern is easily found in the regional climate simulation as shown in Fig. 1b, where we have taken the vector difference between the afternoon (1700 LST) and early morning (0500 LST) winds at 10 m agl. Clearly shown is that a strong convergent circulation exists focused upon the Continental Divide. This large-scale plateau circulation system is important for transporting tropical moisture into the Southwest from both the Gulf of Mexico and the Pacific Ocean. The convergence from this diurnal circulation system also produces general rising motion over the highest terrain, leading to thunderstorm development and convective precipitation. The manifestation of this process can only be adequately represented at higher resolution, as shown below.

The results from the coarse outer grid show that even at the largest spatial scales a strong diurnal response to terrain heating is evident over the mountainous portion of western North America. Now we turn our attention to the Southwest, where this strong diurnal circulation has a more complicated structure due to the numerous mountain ranges and valleys that actually comprise the smooth-appearing Rocky Mountain massif on the outer grid as it was shown in Fig. 1. The nine-month average afternoon (17 LST) wind field at 10 m agl over the inner nested grid (20 km) of the regional climate simulation is shown in Fig. 2a. Here, the tendency for more localized convergent flow toward the highest terrain is clearly evident. In Arizona, the low-level afternoon flow direction is generally from a southwest direction at about 5 m/s. This flow draws tropical moisture from the Gulf of California into the desert Southwest and northward along the Colorado River into southern Utah and western Colorado. East of the mountains, south-southeast flow advects moisture from the Gulf of Mexico up the Great Plains and into the eastern side of the Rockies. These two moist wind systems converge over the high terrain of Colorado and New Mexico. As a result, both of these states show a high degree of convective storm activity on average at this time (Fig. 2b). This activity is most intense along the Front Range in Colorado and the Sangre de Cristo Range in New Mexico, as well as along most of the other smaller ranges in central New Mexico. Another region of intense convective activity is southeastern Arizona, due to its proximity to the Gulf of California and moisture transport from strong Mexican storms along the Sierra Madre Occidental.
The broad band of widespread convective activity in late afternoon simulated in the model from southeastern Arizona to northern Colorado agrees well with composite satellite imagery over the region [8,9] and with lightning strike studies [10,11]. Areas to the west of this primary band show that convective precipitation is confined to individual mountain ranges. This highly localized activity is due to a lack of moisture or strong convergent flow, and a suppressive large-scale circulation pattern. The pervasive large-scale circulation over the west coast consists of a dominant high pressure system that tends to bring very dry, stable air masses into the Great Basin region. Only sporadically does this high pressure system break down, thereby allowing the Great Basin region to be influenced by atmospheric conditions that are conducive to deep convection. By contrast, in the southern Rockies of Arizona, New Mexico, and parts of southern Colorado, the moist, convergent "monsoonal" flow can persist for much of the summer season.

The diurnal nature of the thermal forcing over the Southwest defines the climatology of the region to a large extent. That this is the case can be demonstrated by looking at the early morning (05 LST) wind field at 10 m agl over the nested grid (Fig. 3a). At this time the winds over the mountainous regions are very complex and generally in a downslope direction, in response to nocturnal cooling of the surface. These winds are also much weaker than the afternoon winds. This general downslope flow creates divergence and sinking motion over the mountain region, while areas of convergence can be found in the lower elevations east of the Rockies and within the low desert valleys in Arizona and Utah. The subsequent convective precipitation that results from this morning wind field is dramatically different from that of the afternoon (Fig. 3b). There is no convection at this hour over any of the high mountain regions, and only very small amounts (ten times less than afternoon) over the high plains east of the mountains and in the low desert of Arizona.

This result agrees well with satellite imagery of the area, and with several studies [12,13] that have documented the propagation of convective storms from their afternoon genesis over the mountains of the Colorado Front Range eastward over the plains during the following evening. Another study [14] has shown that Phoenix, in the low desert of Arizona, has a midnight precipitation maximum in summer, due to the migration of storms off of the surrounding mountains and convergent airflow that evolves over the low elevation valleys due to cooling of the mountain slopes.

The modeling system development and results of the nine-month simulations funded by this project are presently being prepared for publication. With our Scripps collaborators, we are also using these modeling results for a more rigorous validation of the regional climate simulation through statistical evaluations with independent surface and rawinsonde data.
References


Figure 1. A regional air-monitoring system climate simulation of June, July, and August 1989-91. (a) Outer grid averaged potential temperature difference field (1700 - 0500 LST) at 1700 m above ground level. Contour interval is 0.5 K. (b) Outer grid averaged wind vector difference field (1700 - 0500 LST) at 90 m above ground level. Maximum wind vector is equal to 10.9 m/s.
Figure 2. (a) Inner grid averaged wind vector field at 10 m above ground level for 1700 LST. Maximum wind vector is equal to 6.1 m/s. (b) Simulated average convective precipitation rate (mm/hr) at 1700 LST. Contour interval is 2 mm/hr.
Figure 3. (a) Inner grid averaged wind vector field at 10 m above ground level at 0500 LST. Maximum wind vector is equal to 3.0 m/s. (b) Simulated average convective precipitation rate (mm/hr) at 0500 LST. Contour interval is 0.3 mm/hr.