

Modeling and Simulation of Spatial and Temporal Precipitation Patterns in Coastal Mountainous Regions – The Case of Northwestern Colombia

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Abstract. Regional and local weather patterns are strongly affected by macroclimatic phenomena. In tropical South America, hydroclimatological behavior is affected by such factors as the meridional oscillation of the Intertropical Convergence Zone, the dynamics of Pacific and Atlantic oceans, the Amazon jungle, and the orographic barriers of the Andes mountains. Interactions between these factors at different space and time scales are complex and non-linear, in particular for the region of northwestern Colombia, one of the rainiest regions of the world. In addition, the El Niño/Southern Oscillation (ENSO) phenomenon is recognized as the dominant mode of inter-annual climate variability in the region (*e.g.*, ENSO variability explains about 50% of the observed variance of Colombian hydrology beyond the annual cycle when a linear relationship is assumed). To capture these non-linear interactions and their impact on precipitation, CSU's Regional Atmospheric Modeling System (RAMS) has been used to perform representative simulations of precipitation cycles in Colombia. CSU-RAMS has been implemented using a nested set of two grids. Input data for initial and lateral boundary conditions were from National Center for Environmental Prediction reanalysis products. Results illustrate the challenges in modeling these non-linear interactions, especially the significant impact of local relief, and the great importance of capturing the diurnal cycle in defining the magnitude and the spatial and temporal patterns of precipitation. It is expected that this physically-based modeling technique will lead to increased understanding of hydroclimatic patterns that can be used for regional and local socio-economic planning and policy making in the contexts of hazard mitigation and optimal use of water resources in Colombia.

1 Introduction

Modeling the spatial and temporal distribution of precipitation is one of the most challenging problems in hydrometeorology. The precipitation process involves complex non-linear interactions among climate, soil, vegetation and orographic characteristics, all of them varying in space and/or time. In the tropics, the atmosphere is mainly thermally driven by latent heat released in deep convective clouds. In tropical South America, particularly Colombia, the main heat source is the Intertropical Convergence Zone (ITCZ).

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The annual movement of the ITCZ controls the annual distribution of rainfall while the spatial distribution is controlled by factors like the Andes Mountains, the Amazon basin and the tropical Pacific Ocean among others. As a result of interactions among these factors, precipitation is extremely variable in space and time. For example, according to Velasco and Fritsch (1987), the west coast of Colombia is the most active area in the Americas and in low latitudes for development of deep convection due to a combination of warm water, orographic lifting and large-scale, low-level macroscale convergence resulting from the interactions of the trade winds. Furthermore, climate variability in Colombia is enhanced by the El Niño/Southern Oscillation (ENSO) phenomenon. This phenomenon is recognized as the dominant mode of the inter-annual climate variability in and over the tropical Pacific Ocean. See for example, Rasmusson and Wallace (1983), Rasmusson and Carpenter (1982), or, Horel and Wallace (1981).

One of the main climatic characteristics of Colombia is that the diurnal range of temperature, which generally is less than 10 degrees Celsius, is greater than its annual range measured as the temperature difference between the hottest and the coolest months, which in general is less than 5 degrees Celsius, (Snow, 1976). In a general sense, two seasons, one dry that occurs from December through April, and the other wet from May through November, characterize Colombia. The annual (temporal) distribution of rainfall, directly dependent on the position of the Intertropical Convergence Zone (ITCZ), is unimodal or bimodal depending on the region. Geographically, Colombia can be partitioned into five zones, namely the Caribbean, the Andes, the Llanos, the Amazon, and the Pacific Coast zones. The Caribbean zone in northern Colombia is characterized by lowlands and an average annual precipitation of about 1500 mm/yr. The Sierra Nevada of Santa Marta, located in this zone, has elevations reaching 5800 m above sea level. The maximum annual rainfall on this region is about 4000 mm/yr and occurs on the western slope (lee face) of the Sierra Nevada of Santa Marta, while the minimum annual rainfall is about 300 mm/yr and occurs on the northeastern section, the Guajira Peninsula. The Andes Mountains zone has an average annual precipitation of 1500 mm/yr. The northwestern section of this zone is the rainiest, reaching up to 6000 mm/yr. The Pacific Coast zone, between the shoreline of the Pacific Ocean and the Western range of the Andes Mountains, has an average annual precipitation of about 5500 mm/yr. The rainiest region of the American continent is located in this zone, with a maximum precipitation exceeding 13300 mm/yr. Its range of annual precipitation is extremely wide; for instance, the northern and western extremes have around 3000 mm/yr, while the area near the Atrato River reaches more than 10000 mm/yr. The Llanos zone is in the eastern section of the country and its average precipitation is about 2800 mm/yr. Lowlands (100-250 m above the sea level) form this zone with a good density river network draining into the Orinoco River. The Amazon basin zone is located in the

southern section of the country and has an annual average precipitation of about 3500 mm/yr.

Because of the complexity of the interactions among the above factors, and the multiple scale interactions present and affecting climate and precipitation in tropical South America, the scientific community has made great efforts to improve climate predictions by using large-scale, coupled ocean-atmospheric modeling systems. These predictions generally focus on large regions and do not give much information about regional and local behavior. Additional efforts have been made to translate these predictions to local spatial scales by using different kinds of techniques with emphasis on statistically-based tools, see for example Poveda and Mesa (1997, 1996, 1995 and 1993), and Pulwarty et al. (1994 and 1992). Realizing that the relationship between large and regional/local scale atmospheric behavior is highly nonlinear (see for example Moss et al., 1994), the applicability of atmospheric physically-based models has been extended to these regions and scales to complement statistically based models.

This work focuses on the use of the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University (CSU) to perform a representative simulation of spatial and temporal precipitation patterns in the coastal mountainous region located in northwestern Colombia.

2 Data and Methodology

2.1 CSU's Regional Atmospheric Modeling System (CSU-RAMS)

The CSU-RAMS has been developed at Colorado State University with continuous improvements since 1986. By using a telescopic sequence of nested grid domains, CSU-RAMS has the ability to represent non-linear scale interactions, and to transfer information from large general circulation scales to regional/local circulation scales. This modeling system has both non-hydrostatic and hydrostatic formulations that permit representing all meteorologically relevant spatial scales and is capable of modeling micro-scale dynamical systems, cloud microphysical processes, mesoscale systems, and the influence of land surface characteristics on the atmosphere, among others. For a detailed description of RAMS see Walko et al. (1995 and 1999), McQueen et al. (1997) and Pielke et al. (1992).

Input data for initial and boundary conditions are obtained from the standard datasets available four times daily, 00:00, 06:00, 12:00, and 18:00 UTC at the National Center for Atmospheric Research (NCAR). Specifically, for atmospheric variables, the global NMC-NCEP-NCAR reanalysis pressure level data, which is defined on a global 2.5° latitude-longitude grid on seventeen mandatory pressure levels; the global rawinsondes; and the global surface data are used. These data include horizontal wind components, relative humidity and air temperature. Global Sea Surface Temperature (SST) was

obtained from the optimum interpolation (OI) SST analysis that is produced weekly on a one-degree grid by Climate Diagnostics Center (CDC) of National Oceanic Atmospheric Administration (NOAA) (see Reynolds, 1988; Reynolds and Marsico, 1993; and Reynolds and Smith, 1994.) Surface characteristics, global terrain height data and global vegetation type data files are obtained from The Earth Resources Observation Systems (EROS) Data Center (EDC) of the U. S. Geological Survey (USGS). In particular for the digital elevation model of South America, see Bliss and Olsen (1996).

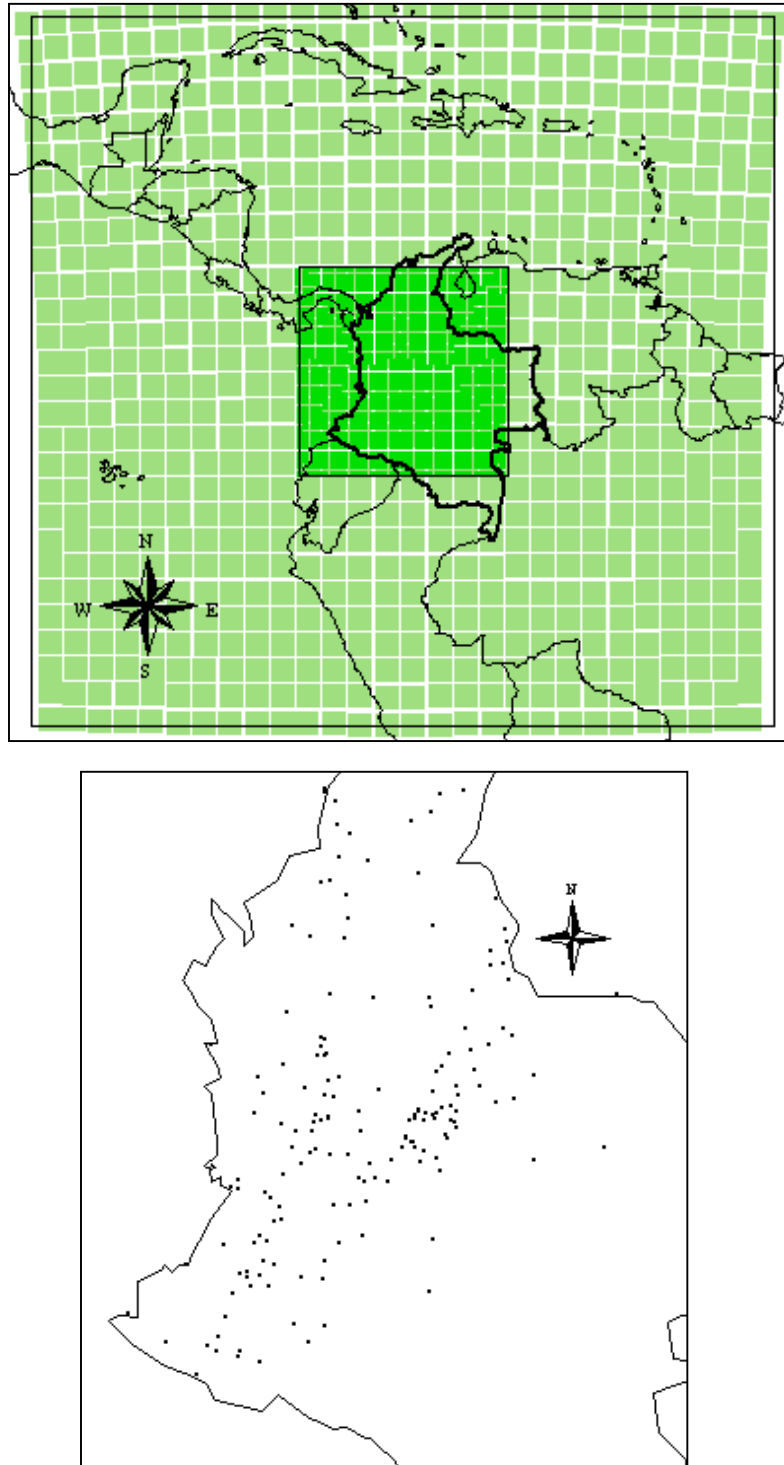
Observed precipitation data from about 250 gauging stations concentrated in the Colombian Andes Mountains were available for this study. Figure 1 shows the location of the rainfall gauges. In addition, other meteorological variables such as temperature, water mixing ratio and pressure fields were compared with the reanalysis data used to obtain the initial and boundary conditions of the simulation.

2.2 RAMS implementation

Two main simulation modes were used in this work. First, a seasonal simulation focusing on the sensitivity of the general characteristics of the spatial distribution of precipitation was done. First semester of 1989, corresponding to a cold ENSO phase, was chosen for this simulation. Second, a daily simulation mode focuses on a detailed temporal distribution of precipitation on a specific zone in the Andes. In this case the period September 25-27, 1998 was chosen.

CSU-RAMS was implemented using a two-grid domain. Both grids were centered over Colombia at 5°N of Latitude and 75°W of Longitude. The coarsest grid was 28x28 grid-points with a 160-km cell size; the finest grid was 34x34 grid-points with a 40-km cell size. Eight soil grid levels, and twenty two and twenty nine vertical levels in the atmosphere for the coarsest and finest grid respectively were used. The vertical grid spacing of the lowest atmospheric level on the domain was 250-m for the coarsest grid. Above this level the vertical grid spacing was increased at a rate of 20% until reaching a spacing of 2000-m, which was set as the maximum vertical grid spacing permitted; after this maximum is reached, the vertical grid spacing is kept constant. Vertical nesting was used in the five lower levels of the coarsest grid to get a smaller height of the lower vertical levels in the finest grid. Then, the first two lower levels of the coarsest grid were split into three levels each and the following three levels into two levels each. As a result of this nesting, the vertical grid spacing of the lowest atmospheric level was around 85-m for the finest grid. Time steps of 120 seconds related with the coarsest grid were used. For the finest grid the time step was reduced using a 1:3 ratio. Figure 1 shows both domains.

Figure 1: Domain of simulation - coarse grid cell-size: 160-km; fine grid cell-size: 40-km.
Position of the gauges used to obtain the observed precipitation maps (About 250 gauges)



Both lateral and top nudging were used. Lateral nudging to the analyzed data on the first seven grid points from the lateral boundary of the coarsest grid with a 1800-second nudging time scale and top nudging above 16-km with a 1000-second nudging time scale. An initial soil moisture condition of 60% saturation in the deepest soil layer and 50 % in the upper soil layer were used. A convective parameterization, bulk microphysics parameterization including only cloud water and rain and the Chen and Cotton short wave and long wave radiation parameterization were used.

The general topographic features of northern South America and Central America are shown in Figure 2, which is a shaded relief image prepared by the USGS. Figures 2 also illustrates the RAMS-topography approximation, on the 40-km grid used in the simulations.

3 Results And Analysis

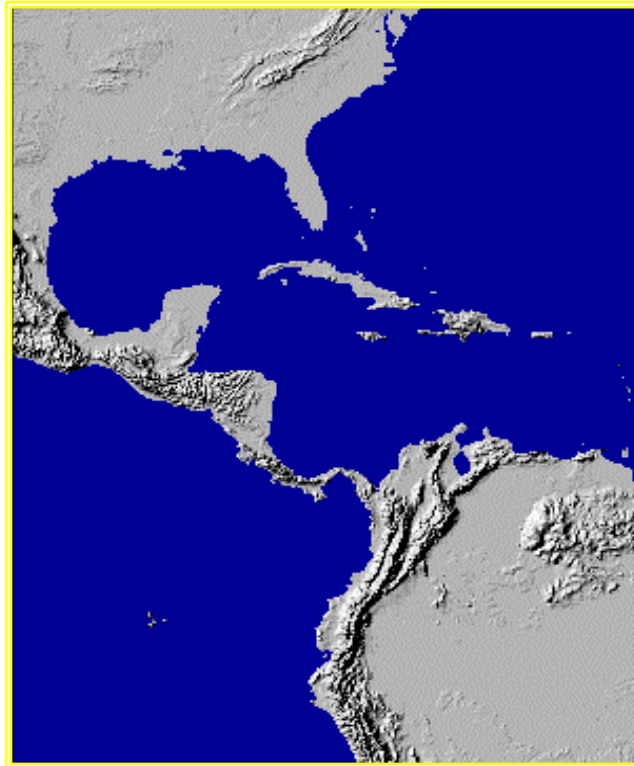
Analysis of results of these two simulation modes will focus on the temporal and spatial distributions of precipitation over the western Andes Mountains of Colombia. In these analyses, it is necessary to keep in mind that model results need to be considered as area or volume averages, while the actual rawinsondes or surface data are point measurements. In addition, even though the model used here is a physically-based model solving the basic equations of fluid dynamics, many of the processes are represented by parameterizations that force model results to be strongly dependent on the number of model assumptions. Here, first we will compare model results with the data used to produce the initial and boundary conditions for the simulation to check that the model is preserving the general patterns; second, we will concentrate on the model precipitation output from the second grid, and the base of reference will be the hydrologic surface data available from Colombian gauges.

3.1 Pressure and temperature fields after six months of simulation












Figure 3 shows pressure results for vertical level at about 0.8-km of height. The upper plot of this figure corresponds to reanalysis data and the lower plot corresponds to simulated data after six months of simulation. All plots are from June 30/89 at 24:00 hours UTC. As expected, pressure fields are simulated relatively well even after six months of simulation as compared to reanalysis data for all levels. It is clear that the Andes mountain range has a large influence on the spatial distribution of pressure.

Figure 4 shows temperature results for the same vertical level above. These figures show that the simulation reproduces the average behavior of the observed temperature field, but results in central western Pacific tend to be a little colder than reanalysis data, while results in the eastern Pacific tend to be a little warmer. The spatial distribution of temperature in the Andes region

Figure 2: Shaded relief image prepared by the USGS, and RAMS model representation of topography (masl)



topography_2nd

	-17 - 0
	0 - 350
	350 - 700
	700 - 1050
	1050 - 1400
	1400 - 1750
	1750 - 2100
	2100 - 2450
	2450 - 2800
	2800 - 3150
	3150 - 3800

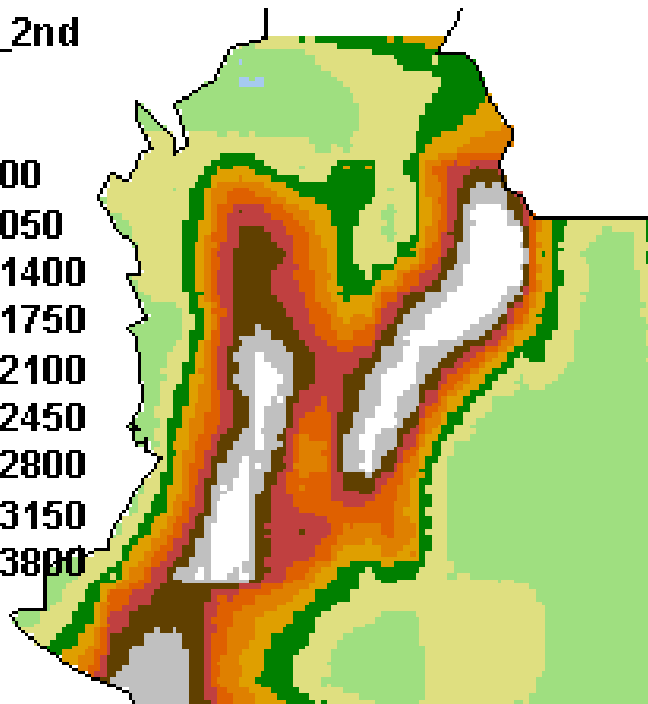


Figure 3. Pressure at 0.8-km of height on Jun 30/89 after six months simulation. The upper plot shows values from reanalysis data and the lower plot shows simulated values. Units are in mb

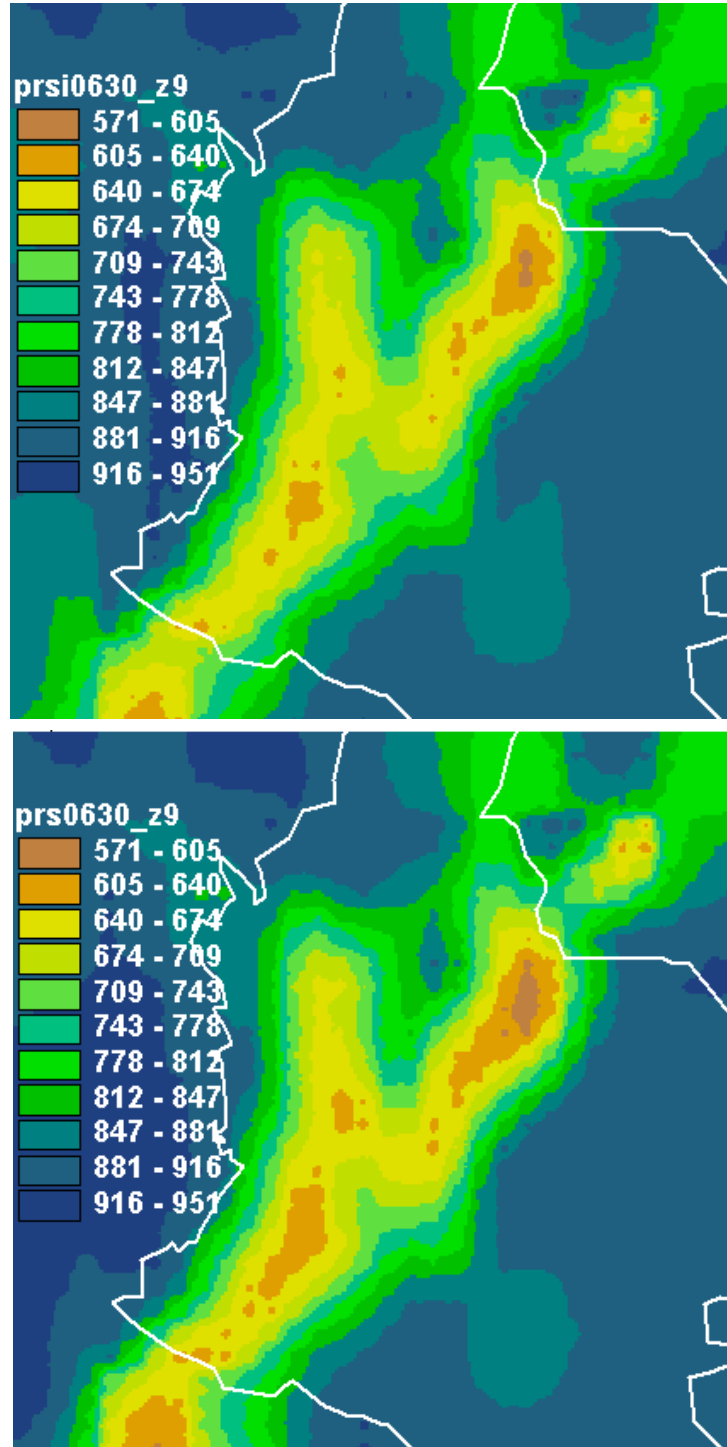
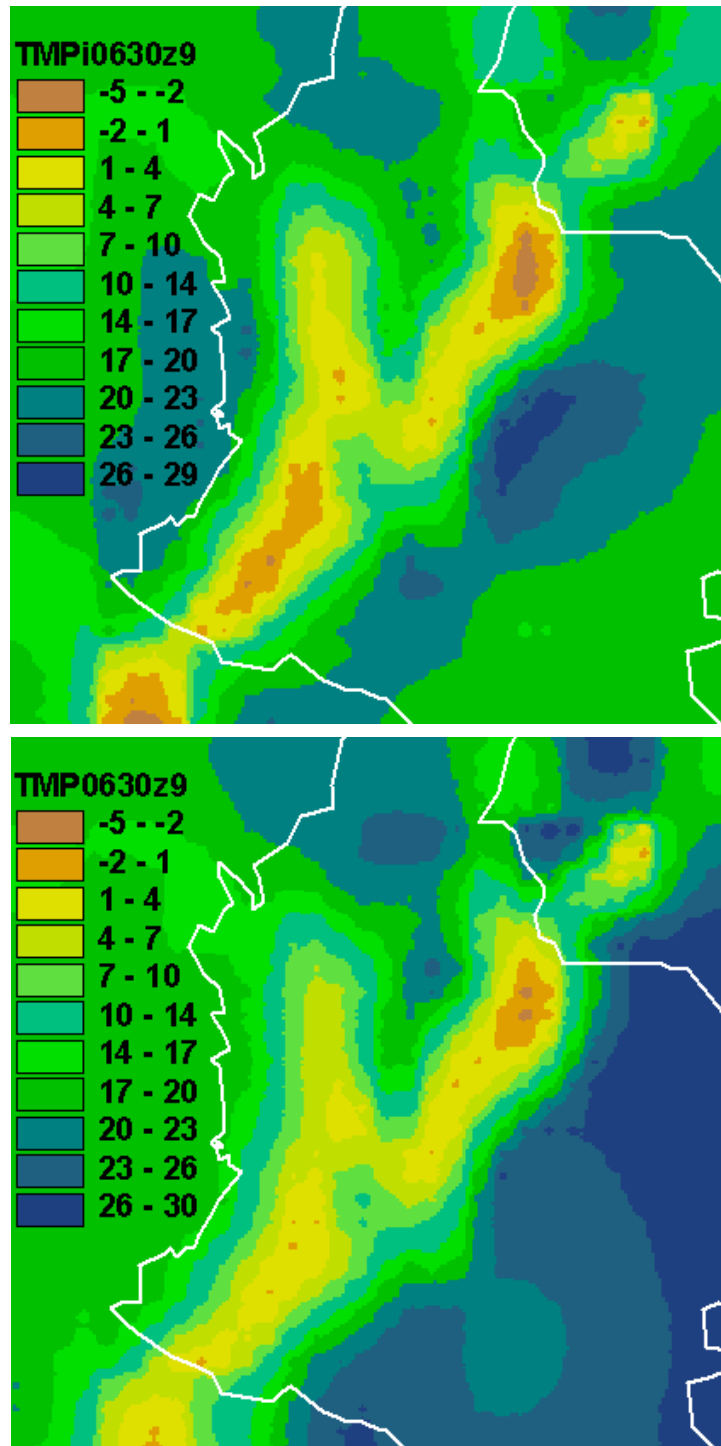


Figure 4. Temperature at 0.8-km of height on Jun 30/89 after six months simulation. The upper plot shows values from reanalysis data and the lower plot shows simulated values. Units are in degrees Celsius.



seems to be acceptable; the small discrepancies could be associated with the better representation of the topography in this RAMS domain than in reanalysis data. As for pressure, it is clear that the spatial distribution of temperature is highly related to the Andes mountain ranges.

3.2 Total water mixing ratio field after six months of simulation

Figure 5 shows total water mixing ratio results at about 0.8-km of height. The simulated total water mixing ratio (lower plot) has an acceptable representation when compared with reanalysis data (upper plot), but, in general, reanalysis data show larger values of total water mixing ratios. There seem to be two regions of major discrepancies: one is on the western Pacific and the other is in the Llanos region of Colombia.

Examining the water mixing ratio and relative humidity at a vertical level around 3.7-km of height, the role that the Andes mountain range plays in the spatial distribution of these variables even at this height is clear. The simulation shows high values of water mixing ratio on the western Pacific and high values of relative humidity agree well with regions of high precipitation values (see Figure 7).

3.3 Precipitation field – seasonal simulation

Plots showing observed and RAMS precipitation fields are presented for one month and six months (January-June, 1989), from the beginning of the simulation. In general, results show that the model reproduces fairly well the spatial and temporal distribution of precipitation in the western region of Colombia. It should be noted and emphasized that western Colombia is one of the rainiest regions of the American continent, exhibiting annual precipitation amounts of up to 13300 mm/yr (Snow, 1976) close to the Atrato river and, according to Poveda et al. (1997), the Atrato river has one of the largest water productions per unit area in the world.

The upper plots of Figure 6 and Figure 7 show accumulated observed precipitation values for one and six months, respectively. For this period, three zones of high precipitation were observed. All three zones are located in western Colombia close to the Pacific coast. Accumulated precipitation values in these zones had values of over 3000 mm and at least one of the gauges registered more than 9000 mm during the six months.

The lower plots of Figure 6 and Figure 7 show that the simulation produces two main zones of high precipitation in western Colombia close to the Pacific coast. One of these zones matches very well with the observations, while the other is offset somewhat from the observed position. There are two other zones clearly defined by the simulation, one of them matches well with the observed distribution in western Colombia, but the other one located in

Figure 5. Total Water Mixing Ratio at 0.8-km of height on Jun 30/89 after six months simulation. The upper plot shows values from reanalysis data and the lower plot shows simulated values. Units are in g/kg

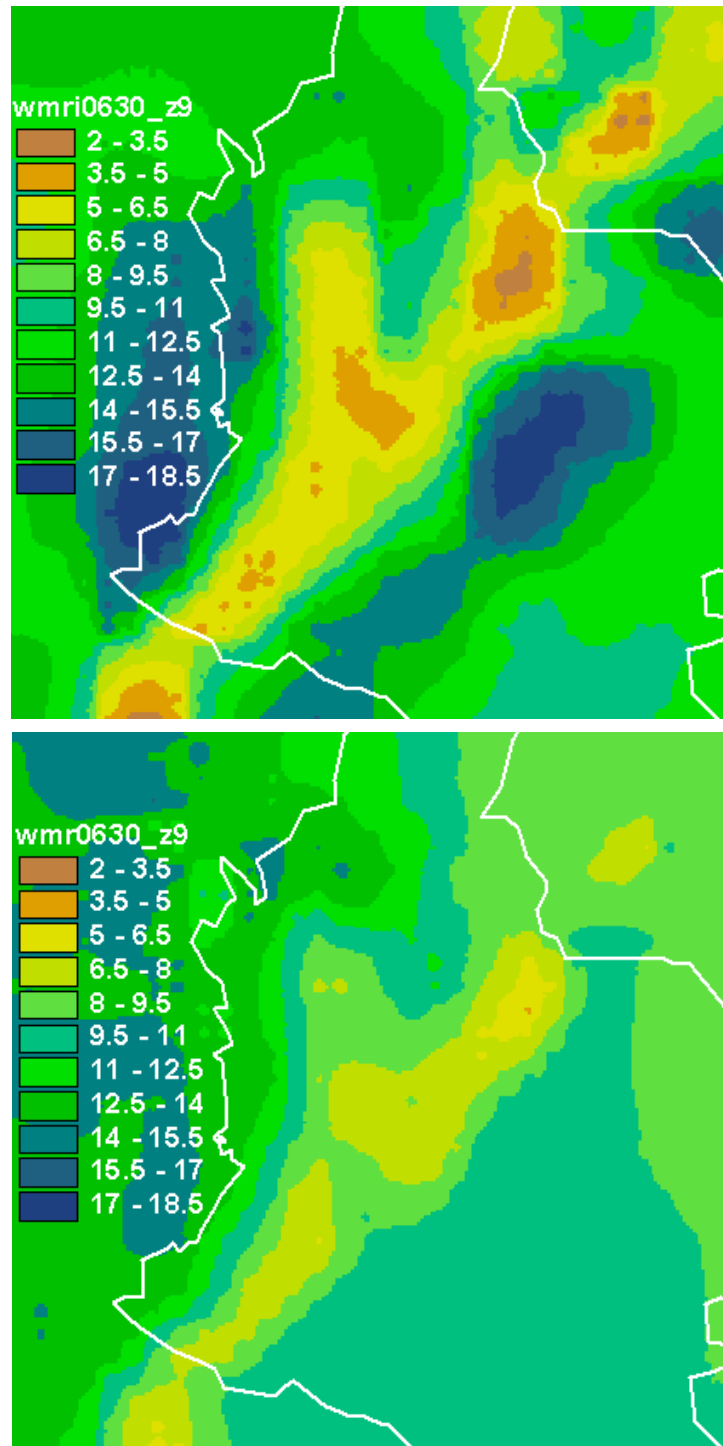


Figure 6. Precipitation from January 1989. The upper plot shows observed values and the lower plot shows simulated values. Units are in mm

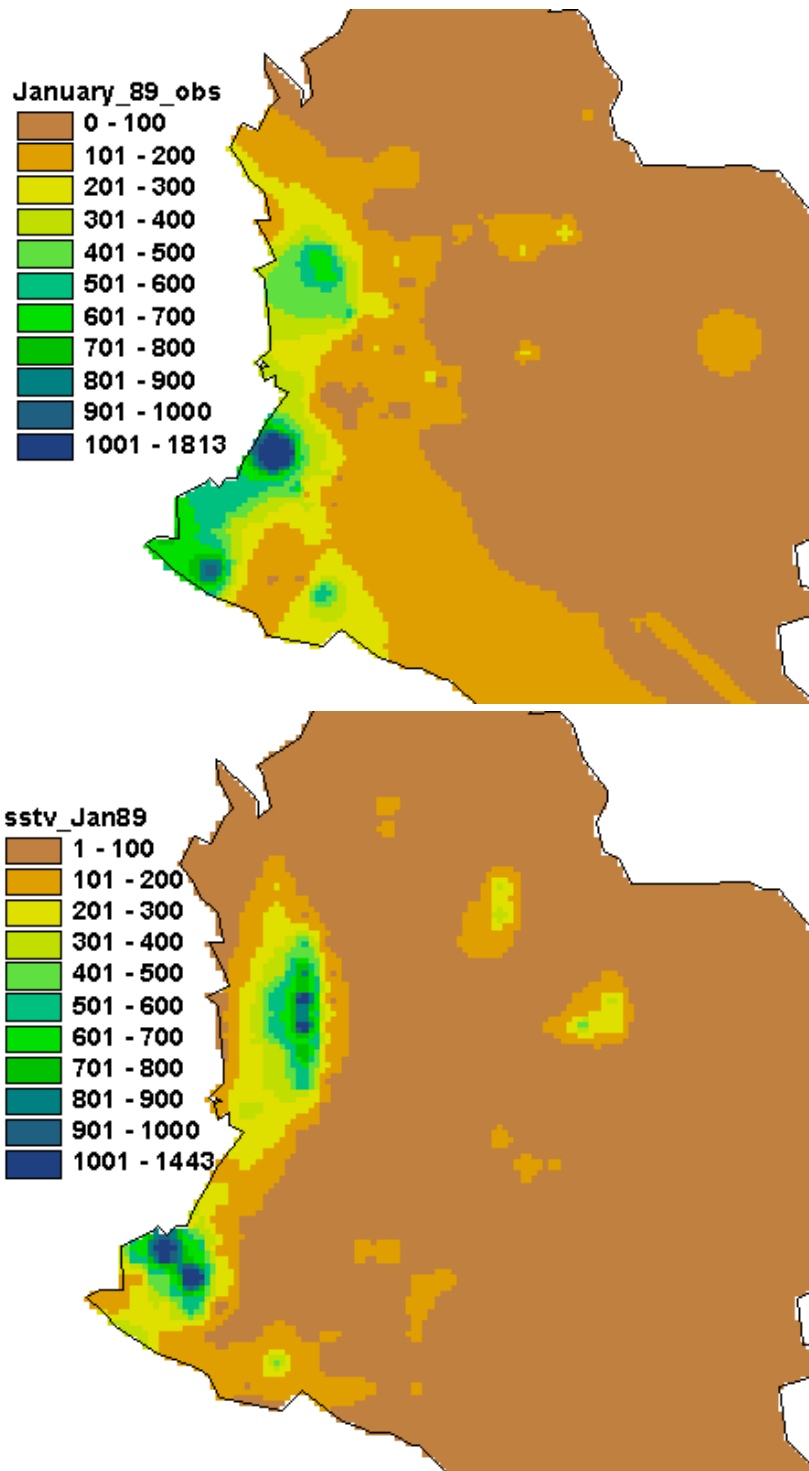
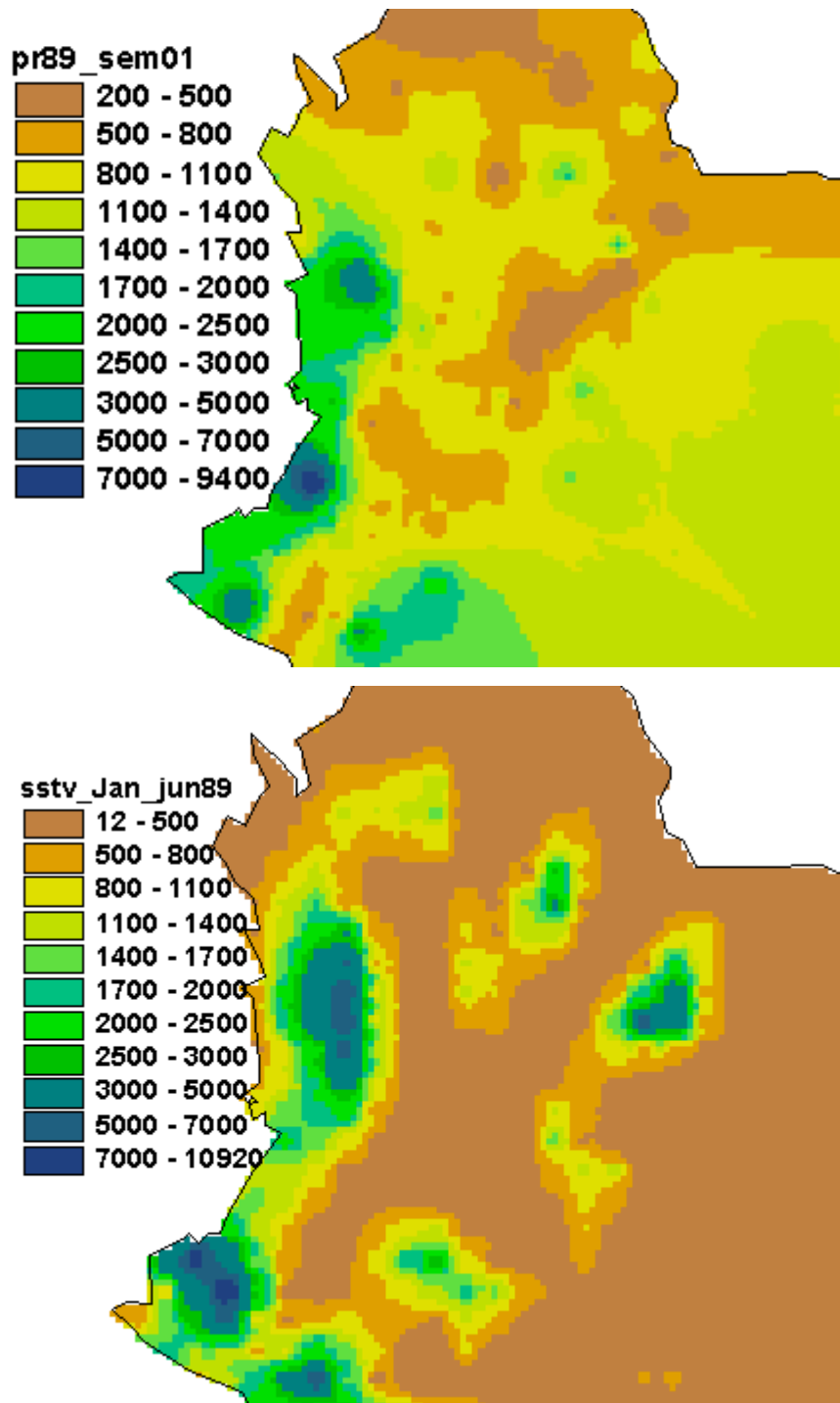


Figure 7. Precipitation from January -June of 1989. The upper plot shows observed values and the lower plot shows simulated values. Units are in mm



central-eastern Colombia does not have a corresponding zone in the observed data; however, given the lack of observational data in eastern Colombia, no conclusions or inferences can be drawn.

Focusing on changes along the six months of simulation, a large area of central and eastern Colombia, outside of the Andes ranges, exhibits values of precipitation no larger than 100-mm, both in the simulation and in the observations. After three months into the simulation, simulated values showed that a large percentage of this area still had low precipitation, with amounts no larger than 200-mm and three well-defined zones appear with values of precipitation reaching 600-mm and more, while observed values showed most of this area with values no larger than 400-mm. Six months after the beginning of the simulation, simulated values were no larger than 500-mm outside of the regions of high precipitation, while observed precipitation showed values around 1000-mm. In this analysis it is necessary to take into account that the gauge stations are very sparse in the eastern portions of the simulation domain (*e.g.*, what the plots are showing as observed values could be very different from the actual values.)

Precipitation model results include contributions from the convective parameterization and from the bulk microphysics parameterization. Figure 8 shows the individual contribution from each parameterization to the total precipitation. The upper image of Figure 8 shows the contribution from convective parameterization while the lower image that from bulk microphysics parameterization for January of 1989, after one month of simulation. It is clear that, for regions of high precipitation amounts, the bulk microphysics parameterization dominates, making the largest contribution to the total precipitation. The spatial distribution produced by the two parameterization schemes along the western range of the Colombian Andes, next to the Pacific Ocean, is similar and can be explained by the interaction between the trade winds and that mountain range (*e.g.*, Snow 1976). However, the associated magnitudes are quite different. While the convective scheme produces values of precipitation around 250 mm, the bulk microphysics parameterization produces two regions of high concentration of precipitation reaching values higher than 1000-mm. These regions of high precipitation amounts correspond closely to those identified in the observations. The same behavior as that described above for one month of simulation is evident after three and six months of simulation.

3.4 Diurnal cycle

Figure 9 shows a longitude-time diurnal cycle of GOES Precipitation Index (GPI), averaged over the 5°N to 7°N latitude band. It shows that the western Andes of Colombia around 78°W to 76°W of longitude presents a maximum of convection during the early morning hours. Figure 10 shows the simulated diurnal cycle of precipitation for September 25, 26 and 27 of 1998

Figure 8. Contribution of convective parameterization and bulk microphysics parameterization to total precipitation for January of 1989. The upper plot shows convective precipitation and the lower plot shows bulk-microphysics precipitation. Units are in mm

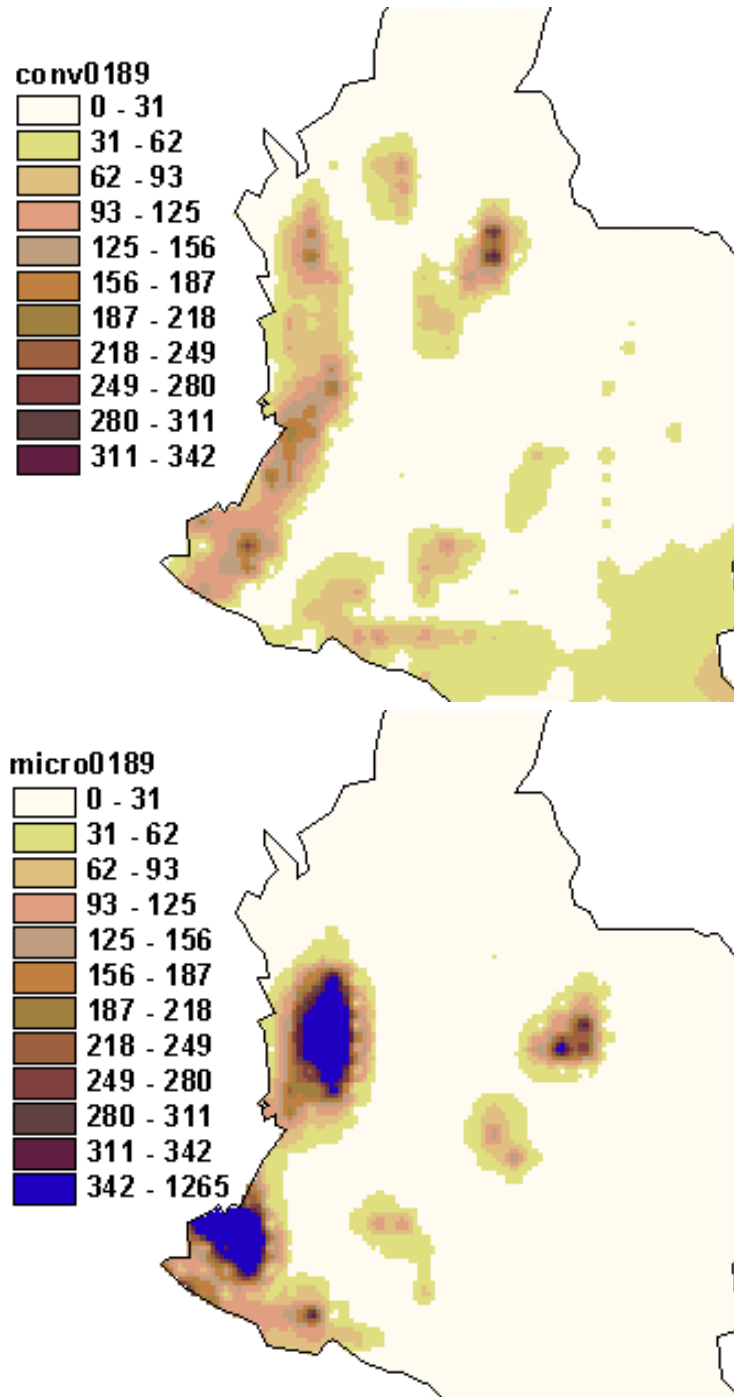


Figure 9. Longitude - Time GPI diurnal cycle. Plot corresponds to an average over the 5N-7N latitude strip (Brian Mapes, NOAA).

GOES Precipitation Index (GPI) 0-1

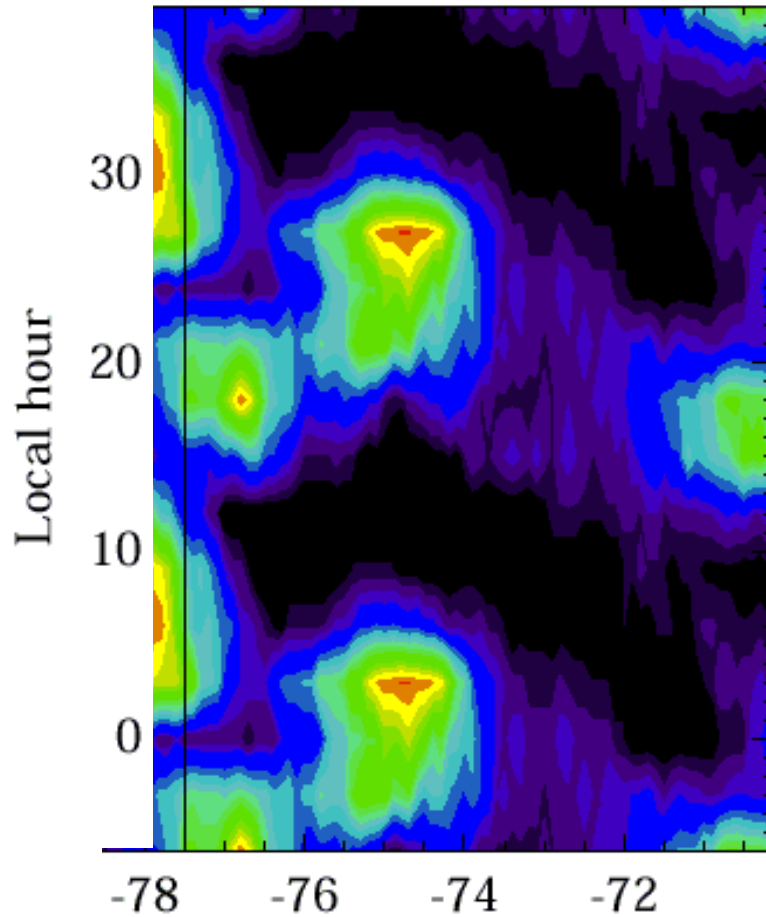
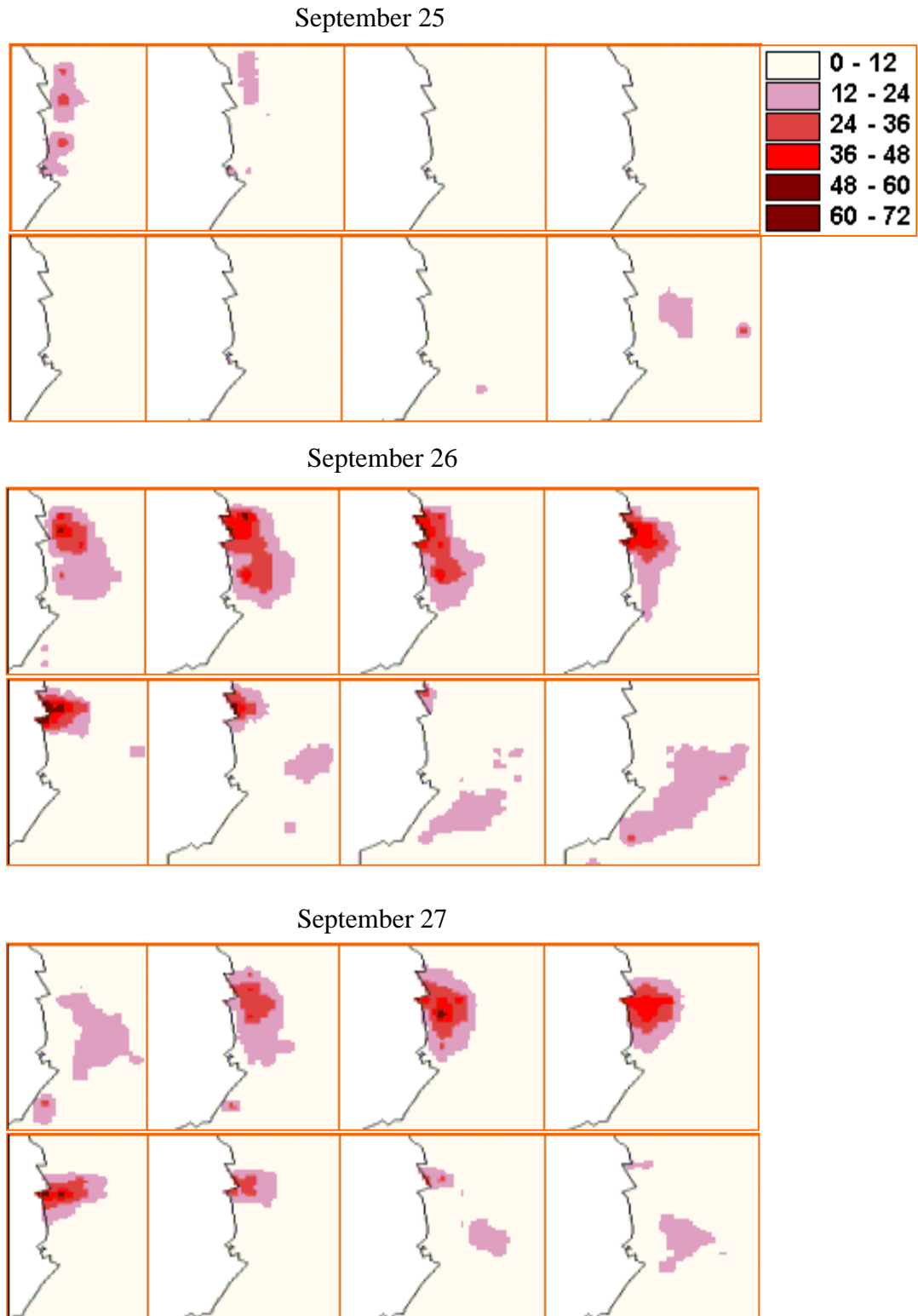


Figure 10. Simulated diurnal cycle of precipitation for September 25, 26 and 27 of 1998. From left to right, from top to bottom and starting on September 25 at 0:0 Colombian hour, plots correspond to 3-h cumulative values in mm.



over the western Andes of Colombia. It is clear from these plots that in a general sense the simulated diurnal cycle resembles the observations.

4 Discussion

Observations and simulation data exhibit fairly similar spatial and temporal distributions of precipitation for the period simulated. For the first simulation mode, at the end of the first, third, and sixth month of simulation, the model precipitation results reproduce quite well in a general sense the spatial and temporal distribution of observed precipitation. Although simulated amounts of precipitation exceeded observed amounts in regions with high concentrations of precipitation, the spatially-averaged precipitation amount was reproduced relatively closely by the simulations. For the second simulation mode, the diurnal cycle of precipitation simulated by RAMS seems to be in agreement with the diurnal cycle observed by satellite measurements.

Results of this application of RAMS in Colombia show the great potential of using this tool for regional climate forecasting at least one season ahead. However, these results have shown also that there is still much work to do, in particular with respect to the definition of the optimal domain configuration, the description of initial and boundary conditions, and convective and radiative model parameterizations to improve simulation results. Clearly, given the marked influence of topography, one of the most important aspects to examine is a detailed review of the land surface characteristics of the region with emphasis on the representation of the Andes Mountains to assure a good correspondence between the actual relief and the RAMS approximation.

The main purpose of this methodology of implementation is to determine the effects of macroclimatic phenomena and general climatic circulation on the regional and local hydro-climate system of Colombia. As expected, the spatial distribution of precipitation in Colombia is highly dependent on the local circulation processes generated by the conjugation of macroclimate circulation with the complex surface features present in the region, (*e.g.*, two oceans, three mountain ranges, a vast region of low lands and the tropical rainforests of the Amazonian jungle.)

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