Proceedings of 8 ICSHMO, Foz do Iguaçu, Brazil, April 24-28, 2006, INPE, p. 429-439.

REGIONAL CLIMATE CHANGE EXPERIMENT OVER SOUTHERN SOUTH AMERICA: PART I: PRESENT CLIMATE CONDITIONS (1981-1990)

Silvina A. Solman *, Mario N. Nuñez and María Fernanda Cabré
CIMA-CONICET/UBA – Dto. Cs. de la Atmósfera y los Océanos (UBA)- Buenos Aires, Argentina

1. INTRODUCTION

General Circulation Models (GCMs) are the most promising tools to determine the response of the climate system to increasing greenhouse gas concentration and to assess how the system will evolve under different emission scenarios. Nevertheless, due to the complexity of these models and the fact that they operate globally, their spatial resolution, typically of several hundred kilometers, is considered insufficient for many purposes. First of all, GCMs are not able to capture adequately the regional-scale features and, in consequence, they are no able to represent the small scale processes and their related heat and momentum fluxes that critically affect the broader scale circulation. Moreover, near-surface variables are strongly influenced by the spatial resolution in which the model operates. This has given rise to different downscaling techniques, being the dynamical downscaling the most physically consistent, though computationally expensive.

After the pioneering works of Dickinson et al. (1989) and Giorgi (1990) the development of regional climate models (RCMs) nested into GCMs has been broadly applied for different applications and different regions. Now, it is commonly accepted that regional climate modeling is the most adequate tool improve the representation of the regional climate. Because they operate on higher spatial resolution (typically 20 to 50 km) they are capable of representing finer-scale details related to thermal contrasts due to complex topography or other surface inhomogeneities. Moreover, due to the fact that RCMs are able to capture more adequately some mesoscale processes, they are expected to simulate more realistically precipitating systems and, thus, regional climate. However, RCMs still exhibit systematic biases due to several shortcomings inherent to the methodology, such as the regional model configuration itself and issues concerning the driving boundary conditions (Liang et al. 2004; Frei et al. 2003; Seth and Rojas, 2003; Moberg and Jones, 2004; Giorgi et al. 2004, among others).

Results form regional climate model simulations over South America are relatively few. Some pioneering studies have been published such as Menéndez et a. (2003), Nicolini et al. (2002); and Figueroa et al. (1995), focused on seasonal simulations. Most recently, Misra et al. (2003) performed some seasonal simulations to explore predictability issues over tropical and subtropical South America. Seth and Rojas (2003) and Rojas and Seth (2003) performed regional simulations in order to explore extreme rainfall anomalies and they analyzed the sensitivity of the regional model to domain size and surface forcing, focusing mainly on the Amazon basin. Xu et al. (2004) explored the effect of the Andes on the eastern Pacific climate. All these studies, based on regional climate models nested in global reanalysis or GCMs, provided valuable information about key concerns regarding systematic biases of regional models over the South American region.

Nevertheless, to date, there is a lack in the literature with results from a continuous long-term simulation allowing the evaluation of regional climate modeling over South America, which represents the first step to build regional climate change scenarios. As part of the Second National Communication of Climate Change for Argentina, three 10-year simulations have been completed over southern South America using the Fith-generation Pennsylvania State University-NCAR (Penn State- NCAR) Mesoscale Model MM5, nested within the Hadley Centre global atmospheric model HadAM3 (Pope, et al., 2000). The simulations cover a present-day 10-year climate conditions (1981-1990) and two future scenarios for the A2 and B2 IPCC emission scenarios (IPCC, 2000) for the period 2081- 2090. The purpose of these simulations is to analyze the regional climate change signal over southern South America and to create a dynamically consistent data base for impact studies. As a first step towards a better understanding of the reliability of regional climate change projections, an exhaustive analysis of the present-day climate simulation is performed. This allows a comprehensive identification and possible interpretation of systematic model biases. The analysis of the reliability of the present-day regional climate simulation over southern South America is presented here while climate change scenario experiments are examined in a companion paper.

Southern South American climate and its variability are dominated mostly by remote, regional and local forcings. The target region extends from the tropics towards the extratropics and high latitudes, being the southernmost part of the region embedded within the westerly circulation. Climate over the region is characterized by interactions of several dynamical processes. The more important regional feature is the complex Andes chain, which extends al along the western coast and is characterized by a narrow barrier channeling the flow in the central part of the region. The ability of the driving GCM and the regional model to capture the climatic circulation features and their relationships to moisture transport and continental rainfall is one of the focuses of the present evaluation.

* Corresponding author address: Ciudad Universitaria Pabellón II- 2° piso (1428) Buenos Aires- Argentina
Tel: 54 11 4787 2693 email: solman@cima.fcen.uba.ar

The objective of this study is to assess the capability of a regional model nested into a GCM to simulate present-climate conditions over southern South America. In particular, we evaluate the simulated seasonal means and the annual cycle of some key climatic variables such as precipitation, daily minimum and maximum temperatures, the variables mostly used in impact assessment studies. The capability of the regional model in reproducing regional circulation patterns is also analyzed in order to better understand model behavior. Possible causes for model biases are discussed.

Though a complete evaluation of a regional climate simulation requires building ensambles of realizations based on different driving GCMs or different members of the same GCM driving the regional model or even by different regional models, this study is intended to provide the major shortcomings and the degree of reliability in simulating regional climate over southern South America. Moreover, due to the limited extension of the simulations, only the analysis of mean climatic conditions, including the seasonal cycle are presented, giving a reasonable idea of the mean climate change. According to Jones et al. (1997) the minimum length needed to obtain an estimate of the climate change signal is ten year due that a 10-year simulation captures about half of the variance of the true regional climate change response.

2. DATA AND METHODS

The regional climate simulation was performed using the Fifth-generation Pennsylvania-State University-NCAR non-hydrostatic Mesoscale Model MM5 (Grell et al., 1993) version 3.6. Menéndez et al. (2004) performed a series of experiments aimed to test the capability of MM5 in simulating climate conditions over the target region, through a set of sensitivity experiments including the response to different convective schemes, surface processes and domain size, driven by “perfect” boundary conditions form NCEP/NCAR reanalysis (Kalnay et al., 1996). The experience gained through these previous studies has defined the most adequate model configuration in order to capture the main climatic characteristics over southern South America.

Regional model configuration used to perform the continuous 10-year simulation includes the Kain-Fritsch convective scheme (Kain-Fritsch, 1993). Planetary boundary layer parameterization is formulated following the scheme by Hong and Pan (1996). Moisture tendencies were calculated by explicit moisture scheme (Hsie et al., 1984) with ice phase processes included. For radiative processes, radiation cooling of the atmosphere accounts for long-wave and shortwave interactions with explicit cloud and clear air (Stephens, 1978 and Garand, 1983). Surface processes are represented by Noah Land Surface Model (Chen and Dudhia, 2001).

The regional model was run in a Mercator grid with 50 km resolution (approximately) in both horizontal directions, with total grid points of 93 (west-east) x 109 (south-north). The integration domain covers southern South American continent, from 15°S to 55°S, including surrounding oceans, from 85°W to 42°W, the in order to avoid lateral boundaries being too close to the region of interest. In the vertical 23 sigma levels were used with the model top at 50 hPa. The land-sea mask and topography and have been derived from the US Navy 10-min resolution dataset. Vegetation and soil properties were obtained from USGS vegetation/land use data base.

Data from the Atmospheric General Circulation Model HadAM3 was used to drive the regional model. HadAM3 is a high-resolution version (1.25° latitude by 1.875° longitude resolution) of the Hadley Centre Atmospheric Global Model. Details on model configuration can be found in Pope et al. (2000). It is worth to mention that, the HADAM3 forcing data was provided on a coarser 2.5° latitude by 3.75° longitude resolution. Lateral boundary conditions were provided in a 6-hourly interval within a relaxation zone in the lateral boundaries. In addition, MM5 also requires the specification of surface boundary conditions, including SSTs and temperature and humidity over land. SSTs are prescribed from the observed OISST data set (Reynolds el at., 2002) monthly mean values interpolated from a 1° resolution grid. Land-surface boundary conditions are prescribed from NCEP database. Monthly percentage of vegetation variations derived from NCEP reanalysis dataset are also prescribed over land. The land surface model included in the regional model also requires additional datasets for initial and time-evolving conditions over land. These include soil temperature and soil moisture for 2 layers below the surface (0-10 cm and 10-200cm).Time evolving values of these variables from NCEP reanalysis database are prescribed.

The present-day regional climate simulation covers a 10-year period from 1981 to 1990. The regional model was initialized at 00Z 1 January 1980 and completed at the end of 1990. The first simulated year is considered as spin-up period to allow stabilization of soil variables from the land surface model (Christensen, 1999).

For the validation of precipitation and surface temperature we used the dataset compiled by the Climatic Research Unit (CRU) of the University of East Anglia (New et al., 1999, 2000). This dataset includes monthly means in a 0.5 degree resolution global grid spanning the period from 1901 to 2001. In the following analysis we compare the CRU data to the MM5 simulation as it has similar spatial resolution. In the comparison of surface variables, precipitation and surface temperatures, the CRU data were interpolated to the model grid and all fields are shown over land only.

For validating circulation variables, we used NCEP reanalysis dataset for the simulated period at a horizontal resolution of 2.5 degree, for the 1981-1990 period.

3. RESULTS

3.1 Low-level Circulation patterns

Lateral boundary forcing on the regional climate model largely determines the simulated surface temperature and precipitation biases. These can result from model formulation deficiencies or LBC forcing errors. Therefore it is worth to evaluate the systematic errors in the driving fields, particularly in the SLP field. We compare the spatial patterns of seasonal means of circulation fields from the HadAM3 model, NCEP and the regional model.

Figure 1 displays mean sea level pressure fields for austral summer (December-January-February, hereafter DJF) and austral winter (June-July-August, hereafter JJA) seasons averaged over the period 1981-1990 as depicted by MM5, HadAM3 and NCEP reanalysis.

In summer the subtropical high over the Pacific is slightly weaker and shifted poleward in HadAM3 compared with NCEP. The subtropical high over the Atlantic Ocean is located further southeastward than in NCEP. The sub-polar low is deeper in HadAM3 compared with NCEP, a common feature in many AGCMs. The orographically-thermally induced depression over northern Argentina, the Chaco low, is not well represented in the driving model, which shows a broader low pressure system extending east of the Andes. The misrepresentation of this low pressure system may be related with the low resolution of the HadAM3 model and thus with a poor representation of topographic features. Nevertheless, the regional model is able to capture the depression, though more extended into Paraguay than in the observations. In the regional model the subtropical high over the Atlantic is shifted poleward, as in the driving model, but is closer to the continent. During winter the subtropical high over the Pacific Ocean is well represented, though east of the Andes the HadAM3 model shows lower pressure than in the reanalysis data. The subtropical high over the Atlantic is more intense in HadAM3 compared with NCEP and slightly shifted poleward and the sub-polar low is deeper, thus, the meridional pressure gradient over subtropical latitudes over the south Pacific and south Atlantic Oceans are larger than in the reanalysis. Sea level pressure is underestimated in the driving model over the continental area south of 30°S. The regional model improves the representation of surface pressure over the continental area, particularly west of the Andes, though some underestimation remains present south of 30°S. Over subtropical latitudes, south of 35°S, sea level pressure is slightly overestimated in the regional model, as in the driving model, compared to reanalysis, thus, the region of strong meridional pressure gradient is shifted equatorward. Overall, the driving model presents important biases in the sea level pressure field, some of them remain in the regional model, though, in general, the regional model is able to improve the representation of many features of the observed patterns, in particular, those related to topography-induced circulations.

One of the main characteristics of the low-level summer circulation over South America is the Low Level Jet (LLJ) along the eastern slope of the Andes. Inspection of the 850 hPa wind fields (not shown) suggests that the HadAM3 model captures reasonably well the structure of the LLJ, but the intensity of the wind is overestimated at the exit region and the Chaco low is misrepresented and thus northerly flow is too extended southward in the model compared with NCEP. The regional model captures the structure of the LLJ reasonably well over Bolivia, but the cyclonic circulation associated to the Chaco low is shifted northeastward its observed position, producing enhanced easterly component over northeastern Argentina and southeastern Brazil. Nevertheless the regional model, though misplaces the position of the Chaco low, is able to improve the representation of this particular circulation feature compared with the HadAM3 model. Due to this misrepresentation of the low-level circulation, the wind pattern over Paraguay, southeastern Brazil, northeastern Argentina and Uruguay presents a large bias in the regional model. The misrepresentation of this circulation feature has a strong impact on the simulated precipitation over that region, as will be discussed later. During winter, the LLJ is also present in both, HadAM3 and MM5, though the intensity of the northwesterly flow over Paraguay and northeastern Argentina is too weak in MM5. At high latitudes, between 40°S and 55°S westerlies over the western coast of South America and over the Patagonia are stronger in HadAM3 and, in consequence in the regional model as well, compared with the reanalysis data. This behavior induces more intense high –frequency systems embedded into the sub-polar storm-track.

In summary, the HadAM3 reproduces the main features of the low-level circulation, but shows some important differences with observations. The regional climate improves the representation of the key climatic circulation features, nevertheless, it fails in reproducing some circulation patterns that are critical in determining the precipitation in subtropical South America. Nevertheless, it is important to keep in mind that regional model biases are due to both, biases in the driving-model and deficiencies in the regional model itself.

3.2 Surface variables

Figure 2 compares the 10-year average seasonal precipitation in the CRU observations and the regional model for austral summer and winter seasons. During summer season, the wet season for most of South America east of the Andes, the regional model is able to represent the broad structure of the precipitation field. The precipitation maximum associated to the South Atlantic Convergence Zone (SACZ) is captured by the model. The precipitation maxima over the Altiplano and over Paraguay and northeastern Argentina, the exit region of the LLJ, are also captured. Nevertheless, precipitation tends to be overestimated, particularly north of 25°S. This can be associated to the fact that the regional model

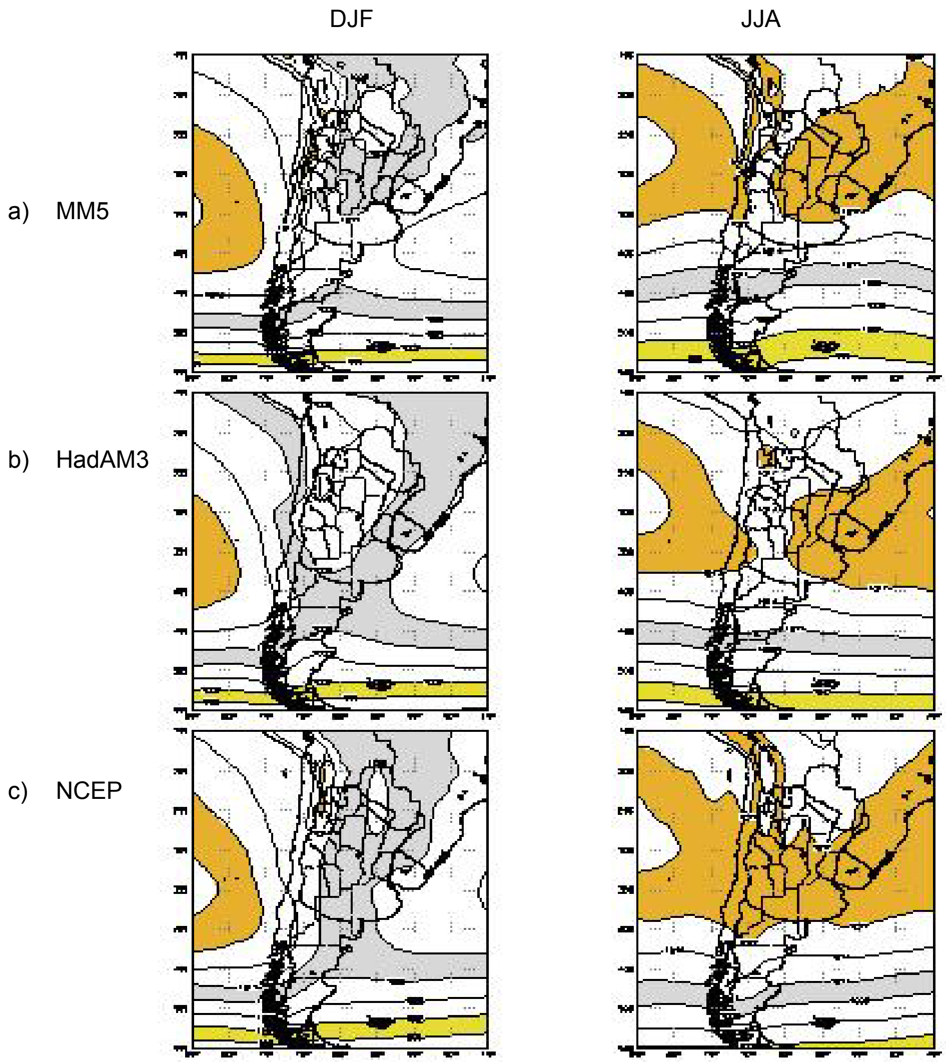

Figure 1: Average sea level pressure (hPa) for DJF (left) and JJA (right) for the period 1981-1990 corresponding to: a) MM5; b) HadAM3; c) NCEP reanalysis. Contour interval is 3 hPa.

misplaces the low pressure center over northeastern Argentina and thus, the advection of moist air and the convergence of moisture flux are misplaced too. Over the central plains, including the La Plata basin, precipitation is underestimated. This is a common feature with previous modeling efforts in the region (Saulo et al. 2000; Menéndez et al. 2004). In the case of MM5, this underestimation can be associated to the enhanced low pressure system located over Paraguay, shifted to the northeast with respect to observations, and the misplacement of the subtropical high over the Atlantic Ocean, inducing easterly flow instead of northeasterly flow over La Plata basin, which is the main source of moisture over the region. Deficiencies in the summer precipitation over subtropical areas in South America, which is mostly convective, may be associated also to deficiencies in model parameterization of convective precipitation and in the representation of land-surface processes. Higher latitudes experiences maximum frequencies of storms crossing the region, associated to the Pacific storm-track centered at 45°S and thus west of the Andes there is a maxima in precipitation. This feature is well captured by the regional model, nevertheless, due to overestimated westerlies in HadAM3 and also in MM5, which induces enhanced synoptic activity, and a more detailed structure of the topography in the latter, the precipitation is overestimated. This is also a common feature of regional simulations over steep mountain regions (Leung et al. 2003). The regional model is also able to capture the dry characteristics over the Argentinean Patagonia region. It is worth to mention that larger biases also exists among observational precipitation databases in the region. For instance, the precipitation over the elevated terrain areas tends to be underestimated in most databases, and direct observations are not available. During winter season, dry conditions over most of the region are also well captured by the model. Over southeastern South America the model underestimates the amount of precipitation. This is related to weaker northwestery winds and misplacement of the subtropical anticyclone over the Atlantic, and thus advection over the La Plata basin is mostly from the west, instead of being northwesterly. The precipitation pattern extended over Central and southern Chile associated with the equatorward shift of the sub-polar storm-track is also captured. Nevertheless, due to larger intensity of the westerlies in MM5 (coming from HadAM3 in the

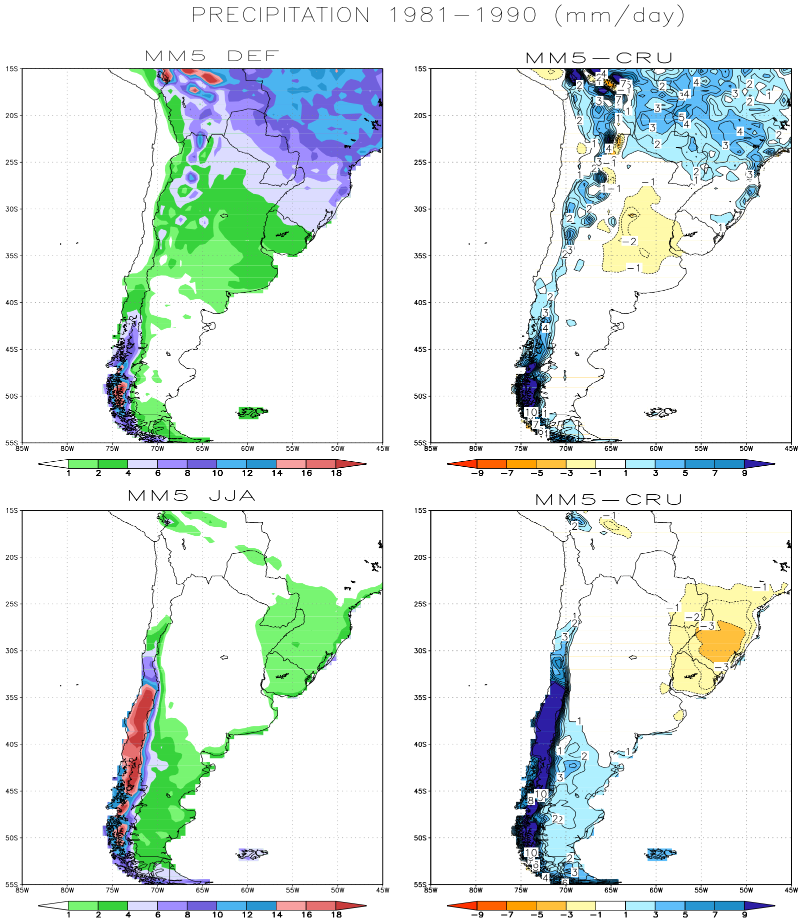

Figure 2: Simulated (MM5) average precipitation for the period 1981-1990 for DJF (top) and JJA (bottom). Left panels display the difference between simulated (MM5) and observed (CRU) precipitation for both seasons. Contour interval is 2 mm/day

western boundary) over a region of high orography, the precipitation is overestimated.

Inspection of the frequency of wet days (not shown), reveals that during summer the simulated number of rainy days is overestimated, 10 to 30 days more than in CRU observations, over southern Brazil, Paraguay and Bolivia. This can be associated to the convective scheme used in this simulation, the Kain-Fritsch scheme, which tends to overestimate convective rainfall amounts. Sensitivity experiments with MM5 performed over South Africa have shown that KF scheme simulates too many rainy days (Tadross, et al, 2006) thus, the positive bias in precipitation is in partly due to a positive bias in the wet day frequency. Nevertheless, this scheme was preferred among others that systematically underestimated precipitation over subtropical South America. Thus, the overestimation of rainfall in that region can be associated to both, the enhanced cyclonic circulation and the effectiveness of the convective scheme over the region. Over central Argentina, the bias in wet days is also positive (10 to 20 days more than CRU), though the total rainfall amount is less than the observed. Besides the weaker moist flux advection from the north, as mentioned previously, it is important to remark that during summer months simulated soil moisture is underestimated over central Argentina (not shown). Drier soils may contribute to weaker latent heat release form the surface and thus rainfall may be underestimated due to less intense but more frequent precipitation events. During winter and transition seasons the main deficiency of the regional simulation is the underestimation of rainfall over the La Plata basin area and central and northern Argentina and overestimation over Patagonia. Over La Plata basin there is a negative bias in the frequency of rainy days and soil moisture, mainly during autumn and spring. Thus, the negative bias in precipitation is not due to deficiencies in rainfall intensity but it can be associated to weaker surface fluxes, and in the availability of moisture due to deficiencies in the position of circulation patterns.

It is important to remark that, in general, regional climate simulations in the state-of-art, present difficulties in the representation of rainfall, they are capable of representing the geographical distribution of rainfall but they are not able in reproducing rainfall amounts adequately. Precipitation is one of the most difficult variables to simulate as it represents a delicate interaction among many processes including surface fluxes, dynamical mechanisms, thermodynamical processes, and radiative processes, all of these possible areas for model improvement.

Figure 3 compares the 10-year average summer and winter surface air temperature in the regional simulation and CRU observations. Overall, the

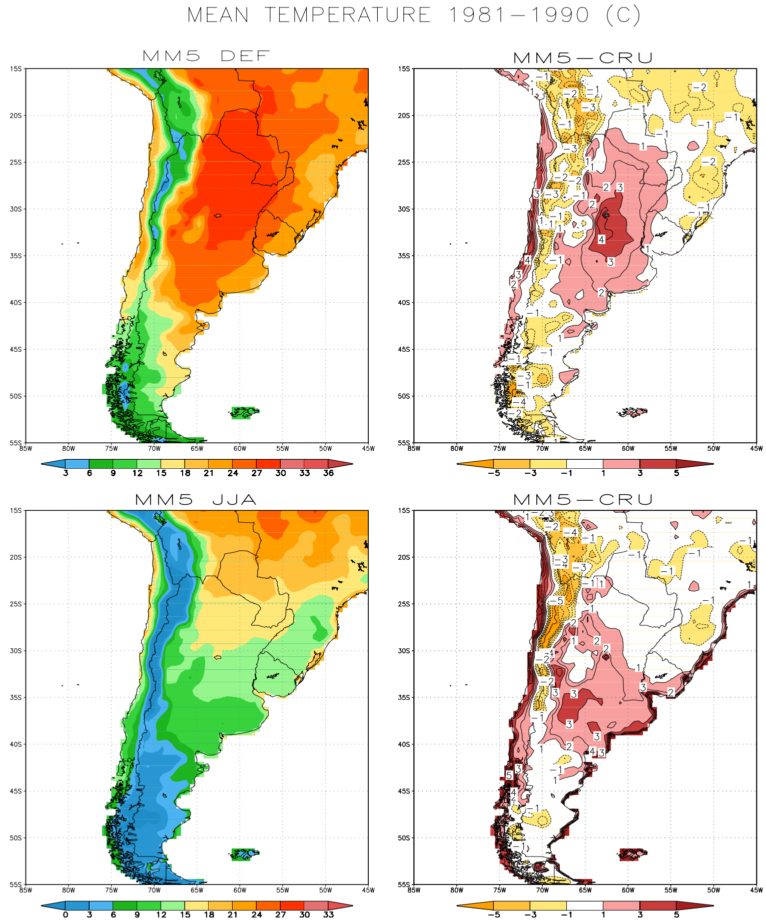

Figure 3: Simulated (MM5) average surface air temperature for the period 1981-1990 for DJF (top) and JJA (bottom). Contour interval is 3°C. Left panels display the difference between simulated (MM5) and observed (CRU) temperature for both seasons. Contour interval is 2 °C

regional model is capable of representing the broad structure of the temperature filed and its seasonal evolution. Nevertheless, some systematic biases are found, such as a warm bias over central and northern Argentina more intense during summer months, a cold bias over mountainous regions, and cold bias over tropical latitudes, particularly during summer. The warm bias over the central plains of subtropical South America is a common feature obtained in several climatic simulations for the region (Misra et al, 2003; Misra et al., 2002). Inspection of soil moisture fields shows that particularly during summer season soils are too dry over subtropical regions of southern South America, thus, drier soils and less rain over subtropical latitudes may induce higher surface air temperatures (Pal and Eltahir, 2001). Southern Brazil is characterized by a cold bias smaller than 2°C. It is worth to mention that the regional model overestimates rainfall and frequency of rainy days in this region, which is consistent with cooler surface air temperature. One last consideration regarding the temperature fields is the cold bias over mountainous regions. This is a common feature of regional climate simulation over different regions of the world (Giorgi et al., 2004). These authors point out that observed data over elevated regions may be affected by a warm bias due to the predominance of stations over less elevated areas (New et al. 2000) and thus, the observed temperature may be underestimated over these regions.

The spatial pattern of biases found for the mean seasonal temperature field are similar for the maximum temperature (not shown). During summer months warm bias over central and northeastern Argentina is more pronounced, as a consequence of the impact of drier soils and less rainfall. Over southern Brazil and Paraguay, wetter conditions induce also more pronounced cold bias. During winter months, the systematic overestimation over central Argentina is less than 2°C and cold biases over Patagonia, where rainfall is overestimated, are below 2°C over most of the region. Over the northern part of the domain the errors in maximum temperature are even smaller.

The spatial structure of model biases for the minimum temperature is different from those found for mean and maximum temperatures. Over almost all the model domain the bias is positive. During summer months positive bias is up to 3°C in some regions over central Argentina and Paraguay. Over high mountain regions the bias is negative, as found for mean and maximum temperatures. Larger overestimation is found during winter season, except over southeastern Brazil. Overall, the spatial distribution of minimum temperature bias is similar to the spatial distribution of the frequency of rainy days bias. This behavior merits further model development in order to improve the representation of both, rainfall and surface air temperatures. Nevertheless, the bias in maximum and minimum temperature are less than 3 degrees over vast areas of the domain, being the maximum temperature, in general, better represented than the minimum temperature. Though the biases are large, similar differences have been found in climate simulations over Europe (Moberg and Jones,2004).

Overall, the regional model reproduces reasonably well the north-south temperature gradients, the spatial structure of the temperature fields, the topography-induced details of the spatial patterns and the seasonal evolution of surface air mean, maximum and minimum temperatures. Model errors in the representation of surface variables are associated to both, errors in boundary conditions and errors in the representation of convective processes and land surface processes. In general, larger biases in the precipitation field are superimposed to larger biases in temperature fields, thus, improvement in the representation of rainfall, may result also in a better representation of extreme temperatures.

3.3 Annual cycle

A detailed analysis of the mean annual cycle for precipitation and temperature over several sub-regions has been performed. Figure 4 displays the simulated and observed annual cycles of precipitation averaged over four selected sub-regions: Altiplano (from 27°S to 15°S and from 67°W to 63°W); Southeastern Brazil (from 22°S to 15° and from 56°W to 45 °W); La Plata basin (from 36°S to 25°S and from 63°W to 55°W) and Southern Andes (from 55°S to 41°S and from 75°W to 72°W). Both modeled precipitation values were calculated taking into account land-only grid points. Precipitation from HadAM3 was interpolated to the MM5 grid. Overall, both models simulate the annual cycle of precipitation in all regions reasonably well. Over Altiplano, and Southeastern Brazil, where the annual cycle of precipitation reaches its maximum during summer and its minimum during winter, rainfall is overestimated during summer months and a better agreement is found during winter months, thus, the amplitude of the annual cycle is overestimated by the regional model. Moreover, the regional model tends to produce greater precipitation than HadAM3 during the rainy season. The simulation of precipitation is sensitive to model resolution and convection schemes (Giorgi and Marnucci, 1996a). During summer months precipitation over regions in the northern part of the model domain is mostly convective, when the main differences between both models is reported. Over the La Plata Basin region both models present more difficulties in simulating the annual cycle of precipitation. The annual cycle of rainfall is characterized by two peaks, during April and November. Nor the regional neither the global model are capable of reproducing this characteristic. Moreover, the major shortcoming of the regional model is the systematic underestimation of rainfall during all months, but more pronounced during transition seasons. Over Southern Andes the annual cycle presents a maximum during winter months. Both models represents the annual cycle but overestimate the winter maximum. CRU observations may underestimate observed rainfall over high elevated regions. Nevertheless, the difference between the regional model and the global model may be due to the difference in model resolution, which enhances the topographic forcing, inducing larger overestimation in the higher resolution simulation.

Overall, the annual cycle of rainfall over the analyzed sub-regions simulated by both, the regional and the global models, are in agreement with observations. In general, the regional model improves the simulation of rainfall amount and its annual cycle, though some difficulties are evident. It is important to remark that over some sub-regions, mainly over subtropical latitudes, the HadAM3 model seems to better agree with observations than the regional model, particularly during summer months, but this apparent improvement in model behaviour is not due to a better representation of the regional circulation features associated to rainfall, but more due to a compensation of model errors in the general circulation model.

Figure 5 displays the simulated and observed annual cycles of mean, maximum and minimum temperature averaged over three selected sub-regions: Subtropical (from 25°S to 15°S and from 67°W to 45°W); Southeastern South America (from 37°S to 25°S and from 63°W to 45°W) and Patagonia (from 55°S to 37°S and from 74°W to 60°W). Over almost all regions the mean temperature is slightly overestimated in the regional model, though the warm bias is smaller than 2°, on average. The overestimation is mainly during the cold season, except for the Subtropical region, where MM5 tends to underestimate the mean temperature. HadAM3 is characterized by surface temperatures colder, compared with both, observations and the regional model. Maximum temperatures are, in general, better represented than minimum temperatures. Biases in maximum temperatures are mostly positive, except over the Subtropical region and Patagonia regions. The possible reasons for this behaviours may be associated to the wet bias reported over those regions. Minimum temperatures are, over all the regions, warmer than observed. The warm bias is particularly large during winter months, and thus, the annual cycle for minimum temperature has smaller amplitude than the observed. Minimum temperature can be overestimated due to several reasons. The higher frequency in wet days over the regions where minimum temperature has larger positive biases may be one of them. Moreover, larger biases in minimum temperature are found, particularly for Patagonia, during the cold season, when larger bias in precipitation where reported. Though the biases in simulating minimum temperatures are large (more than 4° for some regions), the order of magnitude of the error is similar to other reported results (Moberg and Jones,

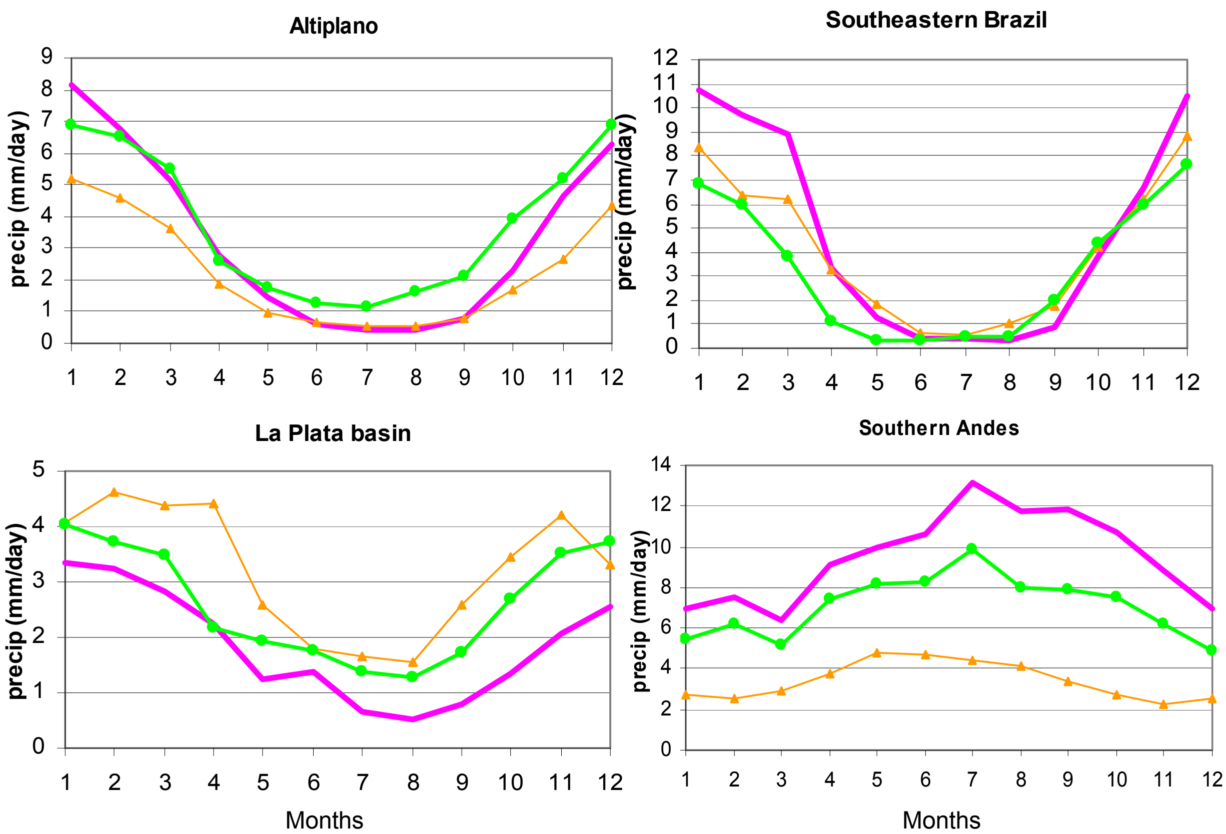

Figure 4: Monthly mean precipitation amount (mm day $^{-1}$) based on observations (orange line), MM5 regional simulation (pink line) and HadAM3 simulation (green line), averaged over the Altiplano, Southeastern Brazil, La Plata basin and Southern Andes regions, defined in the text.

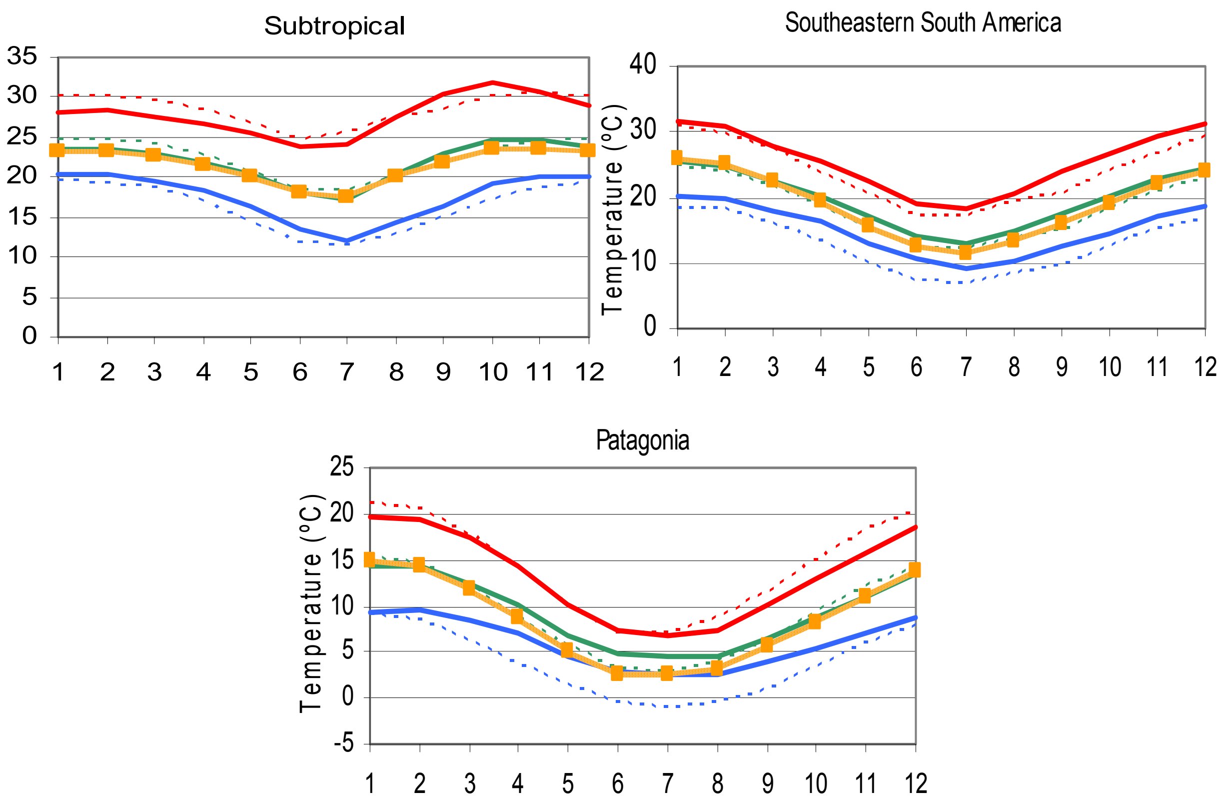

Figure 5: Monthly mean minimum (blue lines), maximum (red lines) and mean air surface temperature (red lines) in °C based on observations (dashed line), MM5 regional simulation (continuous line) and HadAM3 simulation (yellow line), averaged over the Subtropical, Southern South America and Patagonia regions, defined in the text. For HadAM3.only the annual cycle of mean temperature is included.

2004). Nevertheless, although the analyses undertaken here do not systematically diagnose model errors, they provide qualitative information on how biases in the mean temperatures are related to biases in maximum and minimum temperatures. This information is valuable in terms of identifying issues for model improvement.

4. SUMMARY AND CONCLUSIONS

This study presents the results from a regional climate simulation of the present-day climate, corresponding to the period 1981-1990, over southern South America, using the MM5 regional climate model nested within a high resolution version of the Hadley Centre global atmospheric model HadAM3. The analysis of the simulation is focused on evaluating the capability of the nested modelling system in representing spatial patterns of seasonal mean climate and its annual cycle, with two main objectives. First, to quantify the capability of the dynamical downscaling tool to represent present-day climate conditions and to assess the feasibility to produce useful estimates of regional climate change projections. This simulation is the basis to examine the climate change simulations resulting for the A2 and B2 forcing scenarios which are reported in a separate study. Second, to identify critical aspects of regional climate simulation over a barely unexplored region.

The regional simulation reproduces many mesoscale climate features that are triggered by regional forcings, not well captured by the low-resolution driving model. Overall, the regional model improves the representation of the mean climate upon the general circulation model in many aspects. In particular, significant improvements have been found in the regional simulation for near-surface circulation features. The first feature to note is that the regional model exhibits a better performance in the representation of the low-level circulation, not well represented in the driving model, such as the topographically-induced low level cyclonic circulation during summer months over northern Argentina. Nevertheless, it fails in reproducing the correct position of the low pressure system, and, in consequence, this results in a large bias in the precipitation field. The misrepresentation of this system induces a poor representation of the low-level jet, which is critical in determining summer precipitation in subtropical South America, as it serves as conduit of moisture supply from the Amazon basin. Thus, much of the deficiency in the simulation of rainfall may be caused by the deficiency of the regional model in simulating this pattern.

The overall representation of surface variables, such as precipitation, minimum, maximum and mean temperatures are well simulated by the regional climate model. The seasonal mean spatial patterns agree reasonably well with observations, though some model biases have been identified, particularly for some specific sub-regions. For precipitation, biases in the simulation include overestimation over the Andes steep orography, underestimation over La Plata basin during MAM (March-April-May) and SON (September.October-November), and overestimation over Paraguay and southern Brazil during DJF and MAM. Biases over steep orography are due to both, deficiencies in the lateral boundary conditions and the regional model itself. This is a common behaviour in regional simulations over elevated terrain (Leung et al. 2003; Nicolini et al., 2002; Giorgi et al., 2004). It is worth to mention that the data used to evaluate model performance may also be biased, particularly over montanious regions, where precipitation is usually underestimated, making difficult to evaluate properly the model performance. Biases over La Plata basin may be probably due to deficiencies in regional model configuration, with respect to the convective scheme and the land-surface model. Overestimation over Paraguay and southern Brazil may be a consequence of the positive biases in the number of rainy days, associated to the Kain -Fritsch convective scheme (Tadross et al, 2006). The regional model is also able to improve the representation of rainfall over the Altiplano, over the Andes and over south-eastern South America compared with the driving model. Besides the difficulties of the regional model in representing adequately rainfall amounts, it is important to note that the annual cycle of precipitation is well captured over almost all the sub-regions analyzed.

We find that the regional integration quite realistically simulate the observed mean temperatures all over the model domain except over central Argentina, where a warm bias, mostly less than 3 °C, is present all over the year, where we have identified a dry bias in soil moisture content. The regional model performance is generally better during the cold season, while larger biases are found during the warm season. Our analysis also reveals that biases in maximum temperature are smaller than biases in minimum temperatures. Moreover, the spatial pattern of maximum temperature biases is consistent with biases in mean temperature and the precipitation field, except during winter season. The spatial pattern for biases in the minimum temperatures is in agreement with the spatial pattern of biases in wet day frequency. Although there seem to be no consensus of what the cause for temperature biases are, warm biases are usually found over regions where precipitation amounts are underestimated, inducing soils too dry and too little evaporation, thus, the soils tend to warm more efficiently (Moberg and Jones, 2004). This behavior has been confirmed in our simulation, for summer, autumn and spring seasons. Possible improvements in the representation of surface air temperatures are, thus, largely related to improvements in the representation of convective processes and in the representation of surface processes as well.

The analysis undertaken in this study does not systematically diagnose the physical explanation of model errors but it suggests possible tracks for model improvement. Besides the systematic errors of the present-day climate simulation discussed here, the results are encouraging since dynamical downscaling techniques are the most reliable tool to project future projections of climate change with enough spatial detail, as needed by users of regional climate change scenarios for impact studies. However, results of future regional projections of climate change should be taken with care, since, even in the ideal case of a perfect simulation of the present-day climate, the projections are not necessarily more realistic.

*Acknowledgments***.** This work was supported by the IAI Project CRN 055 and ANPCYT Project PICT2002 12246. We like to thank the Hadley Centre for providing the HadAM3P data. We also thank Alfredo Rolla for their invaluable cooperation in running the model.

References

Chen, F and J. Dudhia, 2001: Coupling and advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Wea. Rev*, 129,569-585.

Christensen O.B. 1999: Relaxation of soil variables in a regional climate model, *Tellus*, 51A, 674-685.

Dickinson, R., Errico, R., Giorgi, F. and Bates, G. 1989: A regional climate model for the western united states, *Climate Change* 15, 383–422.

Figueroa, S., P. Satyamurti, and P. L. Silva Dias, 1995: Simulation of the summer circulation over the South American region with an eta coordinate model. *J. Atmos. Sci.,* 52, 1573–1584.

Frei C., Christensen J.H., Deque M., Jacob D., Jones R.G. and Vidale P.L., 2003: Daily precipitation statistics in Regional Climate Models: Evalution and intercomparison for the European Alps. *J. Geophys. Res*., 108(D3), 4124.

Garand, L., 1983: Some improvements and complements to the infrared emissivity algorithm including a parameterization of the absorption in the continuum region. *J. Atmos. Sci*., 40, 230-244.

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., X. Bi, Pal J., 2004; Mean, interannual variability and trends in a regional climate change experiment over Europe.I. Present-day climate (1961-1990). *Clim. Dyn*., 22, 733-756.

Grell, G. A., J. Dudhia and D. R. Stauffer, 1993: A description of the fifth-generation Penn System/NCAR Mesoscale Model (MM5). NCAR Tech. Note, NCAR/TN-398+1A,107 pp.

Hong, S., H. Pan, 1996: Nonlocal boundary layer vertical diffusion in a Medium-Range Forecast model. *Mon. Wea. Rev*., 124, 2322-2339.

Hsie, E.-Y., R. A. Anthes, and D. Keyser, 1984: Numerical simulation of frontogenesis in a moist atmosphere. *J. Atmos. Sci.,* 41, 2581–2594.

Jones**,** R. G., J. M. Murphy, M. Noguer and A. B. King, 1997**:** Simulation of climate change over Europe using a nested regional climate model. Comparison of driving and regional model responses to a doubling of carbon dioxide concentration. *Q. J. R. Meteorol. Soc*. 123:265-292.

Kain, J., J.Fritsch, 1993: Convective parameterization for mesoscale models: The Kain-Fritsch scheme. The representation of cumulus conection in numerical models, K.A. Emanuell and D.J.Raymond, Eds., *Amer. Meteor. Soc*, 246pp.

Kalnay E. y coauthors, 1996: The NCEP/NCAR 40-year reanalysis Project. *Bull. Am. Meteorol. Soc*., 77, 437-471

Leung L. R., Y. Qian and X. Bian, 2003: Hydroclimate of the western United States based on observations and regional climate simulation of 1981-2000. Part I: Seasonal statistics. *J. Climate, 16*, 1892-1911

Liang X. Z.,Li Li, Kunkel K., 2004; Regional climate model simulation of U.S. precipitation during 1982-2002. Part I: Annual Cycle. *J. Climate*, 17, 3510-3528.

Menéndez, C. G., M. F. Cabré, S. A. Solman and M. Nuñez, 2003: Regional climate simulation over southern South America using MM5. *7th International Conference on Southern Hemisphere Meteorology and Oceanography. AMS,* Wellington, New Zealand, 59 – 61.

Menéndez C., Cabré M.F. ,Nuñez M., 2004: Interannual and diurnal variability of January precipitation over subtropical South America simulated by regional climate model, *CLIVAR EXCHANGES* , 29, p.1-3

Misra V., P. Dirmeyer, B. Kirtman, 2003: Dynamic downscalling of seasonal simulations over South America. *J. Climate,* 16, 103-117.

Misra, V., P. A. Dirmeyer, B. P. Kirtman, H.-M. H. Juang and M. Kanamitsu, 2002: Regional simulation of interannual variability over South America. *J. Geophys. Res*., 107(D20) doi:10.1029/2001JD900216.

Moberg A. and P. Jones, 2004: Regional climate model simulations of daily maximum and minimum near-surface temperatures across Europe compared with observed station data 1961-1990. *Clim. Dyn*.,23, 695-715.;

New MG, Hulme M, Jones PD,1999: Representing twentieth-century space time climate variability. Part

I. Development of a 1961-1990 mean monthly terrestrial climatology. *J. Climate,* 12, 829-856

New MG, Hulme M, Jones PD, 2000: Representing twentieth-century space time climate variability. Part I. Development of a 1901-1996 mean monthly terrestrial climatology. *J. Climate,* 13, 2217-2238

Nicolini M., Salio P., Katzfey J., McGregor J.L. and Saulo A.C. (2002): January and July regional climate simulation over South America. *J. Geophys. Res*., 107(D20), Doi: 10.1029/2001JD000736.

Pal, J. and Eltahir, E. (2001) Pathways Relating Soil Moisture Conditions to Future Summer Rainfall within a Model of the Land–Atmosphere System. *J. Climate,* 14: 1227–1242.

Pope V., Gallani M., Rowntree P., Stratton R., 2000: The impact of new physical parameterizations in the Hadley Centre Climate model. *Clim. Dyn.,* 16, 123-146.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. *J. Climate*, 15, 1609-1625.

Rojas M , Seth A., 2003: Simulation and sensitivity in a nested modeling system for South America. Part II: GCM boundary forcing. *J. Climate*, 16,2454-2471.

Saulo, C.A, M. Nicolini and S. C. Chou, 2000: Model characterization of the South American low-level flow during the 1997-1998 spring-summer season. *Clim. Dyn,* 16, 867-881.

Seth A., Rojas M., 2003: Simulation and sensitivity in a nested modeling system for South America. Part I. Reanalysis boundary forcing. *J Climate*,16, 2437-2453.

Stephens, G. L., 1978: Radiation profiles in extended water clouds: II. Parameterization schemes. *J. Atmos. Sci*., 35, 2123-2132.

Tadross, M., W. Gutowski, B. Hewitson, C. Jack and M. New, 2006: Southern African interannual and diurnal climate variability in the MM5 regional climate model. *Theoretical and Applied Climatology*, Special Issue, in press.

Xu, H., Y. Wang, and S.-P. Xie, 2004: Effects of the Andes on Eastern Pacific Climate: A regional atmospheric model study. *J. Climate*, 17, 589-602.