MODELING THE EFFECTS OF THE ANDES ON THE SOUTH AMERICAN SUMMER CLIMATE

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ABSTRACT

To investigate the effects of the Andes on the South American summer climate, a mountain/no-mountain experiment was performed with an early version of the NCEP Eta model nested in simulations of the R40L18 COLA GCM. The Eta model resolution was 80 km in the horizontal plane and 38 vertical levels. The experiment simulated the period December 1, 1991-February 29, 1992. The control run with realistic topography produced reasonable simulation of precipitation distribution and tropospheric circulation. In the absence of the Andes, negligible precipitation was obtained in the southern part of South America, and a new precipitation maximum was produced over Ecuador. The lower- and upper-level circulation were affected, and a drier and colder summer was produced in southern South America. The bulk of the tropical precipitation remained unchanged, and the Bolivian High was well developed. The Bolivian High and the regional upward branch of the Hadley circulation were displaced few degrees north. The subtropical jet was also shifted to the north and weakened. The SACZ was not substantially affected in the no-mountain run. These results are limited by a single experiment, and additional experiments are needed to better explore the effects of the Andes on the South American climate.

Keywords: Mountain/no-mountain experiment; Andes Cordillera; South American climate; SACZ; Eta model; COLA GCM.

RESUMO: MODELANDO OS EFEITOS DOS ANDES NO CLIMA DE VERÃO DA AMÉRICA DO SUL

Para investigar os efeitos dos Andes no clima de verão da América do Sul, um experimento montanha/sem-montanha foi realizado com uma versão antiga do modelo Eta do NCEP aninhado no MCG do COLA R40L18. A resolução do modelo Eta foi de 80 km no plano horizontal e de 38 níveis verticais. Foi simulado o período de 01/12/1991 a 29/02/1992. A integração de controle com topografia produziu uma boa simulação da distribuição de precipitação e da circulação troposférica. Sem os Andes, a precipitação desprezível foi obtida na região sul da América do Sul e um novo máximo foi produzido sobre o Equador. As circulações de baixo e alto nível foram afetadas e um verão mais frio e seco foi produzido no sul da América do Sul. A média da precipitação tropical permaneceu inalterada e a Alta da Bolívia foi bem desenvolvida, mas esta e o componente ascendente da circulação de Hadley na região foram deslocados poucos graus para o norte. O jato subtropical também foi deslocado para o norte e enfraqueceu. A ZCAS não foi substancialmente alterada com a remoção dos Andes. Os resultados descritos aqui são limitados a um único experimento, e outros são necessários para melhor explorar este tema.

Palavras-chave: Experimento montanha/sem-montanha; Cordilheira dos Andes; clima da América do Sul; ZCAS; modelo Eta; MCG do COLA.

1. INTRODUCTION

The Andes are the highest mountains in the Southern Hemisphere, and some of their peaks reach more than 6 km in Bolivia, Peru, and Chile. These mountains are very steep and narrow, and in only few regions they are wider than 500 km. Therefore, the generation of planetary-scale quasi-stationary waves by Andean topography is expected to be small (Lenters et al. 1995). There have been numerous investigations of the effects of the Andes Cordillera in weather and climate (e.g., Nigam et al. 1986; Gan and Rao 1994; Lenters and Cook 1995; Seluchi et al. 1998). Some of these are related to the Bolivian High (BH), which is one of the most important features of the South American summer climate.

The BH is a high pressure center in the upper-troposphere accompanied by a closed anti-cyclonic circulation located over Bolivia around 15°S, 65°W. It is associated with a downstream trough in which subsidence occurs as part of the mechanism that inhibits precipitation over Northeast Brazil (Moura and Shukla 1981). Schwerdtfeger (1976) suggested that the Bolivian plateau—a flat region in the Andes Cordillera of about 100,000 km² with an average altitude of 3,800 m
located in the western part of Bolivia—would be a key factor to form and maintain the BH. His hypothesis was that the Bolivian plateau, acting as a sensible heat source in the middle-troposphere, would help to trigger deep convection, and to establish an upper-level divergent region, i.e., the BH.

However, modelers have shown that the existence of the BH is mostly due to the intense latent heat source associated with precipitation in the Amazon region during the austral summer. Silva Dias et al. (1983), DeMaria (1985), Silva Dias et al. (1987), Kleeman (1989), Gandu and Geisler (1991), and Figueroa et al. (1995) used linear and/or non-linear models with prescribed heat sources to represent convective activity in the Amazon region and investigated the circulation over South America during the austral summer. General aspects of the BH were well reproduced by these models, even when no topography was included. The influence of the Andes was mostly restricted to the lower level circulation.

The South Atlantic Convergence Zone (SACZ) is another important feature of the South American climate that may be affected by the Andes. The SACZ is a well-defined quasi-stationary trough with northwest-southeast orientation extending from the core of tropical South America into the South Atlantic (Kodama 1992). It is characterized by strong moisture convergence, sharp gradient of equivalent potential temperature, and convective activity with rainfall rates comparable to the ones in the Intertropical Convergence Zone (ITCZ).

Satyamurty et al. (1980) suggested that the Andes could be important to the establishment of the SACZ. In their mechanism, the Andes would generate a lee trough over and off the South American east coast. This could slow the propagation of frontal systems and define the location of the seasonal mean SACZ. They used a barotropic model and idealized topography to corroborate this hypothesis. However, Kalnay et al. (1986) using satellite observations and a global model to perform experiments with and without the Andes concluded that the stationary waves in the lee of South America are not of orographic origin. They also found that there is a strong correlation between the latent heat release over the Amazon and the SACZ, and between the South Pacific Convergence Zone (SPCZ) and the SACZ. Later on, Figueroa et al. (1995) identified the importance of the diurnal cycle of latent heat release over the Amazon and Central Brazil during the austral summer to generate the SACZ. They used an eta-coordinate model with prescribed heat source in the Amazon and found a weak low level convergence in the SACZ region. They attributed the preferable position of the SACZ to a joint mechanism induced by the Amazon heat source and by the Andean topography. The basic state trough induced by the convection in the Amazon is also supported by the analysis of Liebmann et al. (1999), who showed that the lowest variance of convection in South American summer is attained in the Amazon.

Several authors have used general circulation models (GCMs) with full physics to address the effects of South American topography and latent heating on the Southern Hemisphere planetary and synoptic scale waves (Manabe and Hahn 1981; Kalnay et al. 1986; Nigam et al. 1986; Schneider 1990; Walsh 1994; Quintanar and Mechoso 1995; Lenters and Cook 1997). GCMs have demonstrated reasonable success in simulating the basic features of the general circulation. However, GCMs have serious deficiencies in simulating regional features because of their relatively coarse resolution and limitations in their physical parameterizations.

High-resolution regional models (RMs) nested in GCM forecasts have been widely used for numerical weather prediction over the world. The improvement of the RM solution over the GCM may be achieved in part because of a better representation of the mesoscale forcing and adequate physical parameterizations. Normally, the atmosphere and surface physics of the RM and the GCM are not the same. This may create inconsistencies between the RM and the GCM atmospheres, but it has not prevented the success of the RMs in simulations and forecasts (e.g., Black 1994; Martin 1998). Also, the dependence of the RM solution on the domain-size and resolution has been explored, as well as its sensitivity to the surface boundary conditions and physical parameterizations (Treadon and Peterson 1993; Gallus 1999; Mass et al. 2002; Tanajura et al. 2003).

In an attempt to improve the realism of the climate simulations produced by GCMs over particular regions, RMs have also been used. Many authors, e.g., Dickinson et al. (1989), Giorgi and Bates (1989), Juang and Kanamitsu (1994), Machenhauer et al. (1996), Ji and Vernekar (1997), Seth and Giorgi (1998), Fennessy and Shukla (2000), among others, have used regional models and illustrated their difficulties and their advantages in comparison to GCMs. However, despite the recent developments, the use of RMs for climate studies and prediction is still in early stages, particularly over South America. Tanajura (1996), Chou et al. (2000), Misra et al. (2000), Tanajura et al. (2003), Chou et al. (2002), Seth and Rojas (2003), Vernekar et al. (2003) have shown that the nested model approach can improve several aspects of the circulation and precipitation variability on the diurnal, intraseasonal and interannual timescales over South America. This may lead to better forecasts and understanding of the regional climate.

In the present paper, the South American climate is further investigated with a RM, the National Centers for Environmental Prediction (NCEP) Eta model, which is here nested in simulations of the Center for Ocean-Land-Atmosphere Studies (COLA) GCM. The main goal of this work is to assess the importance of the Andes on the regional austral summer climate. A mountain/no-mountain experiment for December, January and February 1991/1992 is performed. The control run with realistic topography is compared with the no-mountain run in which all topography over South America was removed in both the Eta model and the GCM.

In sections 2 and 3, description of the models and of the experimental design are presented. Section 4 discusses the major differences observed with and without mountains. Changes in the precipitation distribution, in the upper and lower level circulation, in the Bolivian High, and in the SACZ are examined. Section 5 presents the summary of the main results and the conclusions.
2. THE MODELS

2.1. The COLA GCM

The GCM used in the experiments is the COLA GCM. Only a very brief description of the model is provided here. More details can be found in Schneider and Kinter (1994). The COLA GCM is a sigma-coordinate global spectral model. Here, it was set to the resolution R40L18, which corresponds approximately to a latitude-longitude resolution of 1.8° x 2.8°. Centered finite difference method is applied to the sigma-coordinates, and a semi-implicit scheme is used in time. Lateral diffusion is used with a fourth order differential operator to simulate horizontal sub-grid transfers of heat and moisture on pressure surfaces, and of relative vorticity and divergence on sigma surfaces.

The model uses the simplified biosphere model described in Xue et al. (1991) in which ground temperature, soil moisture, and snow cover are treated as prognostic variables. The parameterization of the solar radiation is after Lacis and Hansen (1974), and the terrestrial radiation follows Hashvardhan et al. (1987). The deep convection scheme incorporates a modified version of the Kuo (1965) scheme, and the shallow convection follows Tiedke (1984). There is a turbulent closure scheme for subgrid-scale exchanges of heat, momentum, and moisture as in Miyakoda and Sirutis (1977) and Mellor and Yamada (1982) level 2.0. Surface wave drag and the vertical distribution of the wave drag due to vertically propagating gravity waves is parameterized following the procedure by Pierrehumbert (1987), Palmer et al. (1986), and Helfand et al. (1987). Boundary conditions given to the lowest model layer include sea surface temperature (SST), sea ice extent, ocean surface albedo, and orography, which is shown in Fig. 1a.

2.2. The NCEP Eta model

The NCEP Eta model is operational in several centers over the world for short-range forecasts (Mesinger et al. 1998; Chou et al. 2002). In the present work, an early version was used. (Black 1994).

Finite difference schemes are applied to the model system of equations in space and time. The discretization of the domain is done with the semi-staggered Arakawa E-grid in the horizontal and the Lorenz grid in the vertical. The following numerical methods are used in the model: (a) a horizontal advection scheme developed by Janjic (1984) that conserves momentum and energy, and restricts the cascade of energy toward the smaller scales; (b) second order nonlinear lateral diffusion depending on the turbulent kinetic energy; (c) a forward-backward scheme for the inertia-gravity wave modified according to Mesinger (1977) and Janjic (1979) to prevent the gravity wave separation; and (d) a split-explicit time differencing.

The resolution used in the Eta model was 80 km in the horizontal and 38 vertical layers, with higher resolution in the boundary layer and in the upper troposphere/lower stratosphere. The time step was 200 s. The domain of the model covered the region 7°W-112°W, 57°S-17°N, centered at 20°S, 60°W, adding up to a total of 12,902 height grid points in the horizontal domain. The E-grid is configured on a rotated latitude-longitude grid in which the center of the grid lies at the center of the integration domain.

The orography is represented by a step-like function in the eta-coordinate system (Mesinger 1984). With this system, well-known errors associated with the determination of the pressure gradient force along a steeply sloped coordinate surface are minimized (Mesinger and Janjic 1987).

The physics of the model contains: (a) a modified Betts-Miller cumulus parameterization (Betts and Miller 1986; Janjic 1994), which is also used for shallow convection; (b) a Mellor-Yamada level 2.5 to account for turbulence between the model layers inside the boundary layer and in the free atmosphere; and (c) a Mellor-Yamada level 2.0 to account for turbulence between Earth’s surface and the lowest model layer. In the Mellor-Yamada schemes, turbulent kinetic energy is calculated at model layer interfaces and is used to compute the exchange coefficients for the transfer of heat, moisture and momentum. Surface fluxes are determined using Monin-Obukhov theory according to Lobocki (1993). The radiation
package uses the schemes of Lacis and Hansen (1974), and of Fels and Schwartzkopf (1975) for the shortwave and the longwave radiation, respectively. Both stratiform and cumuliform interactive clouds are diagnosed (Slingo 1987) based upon the model’s relative humidity and convective rainfall rate. The bucket model (Miyakoda and Sirutis 1983) is used for ground hydrology, and the heat flux from the surface slab into adjacent soil layers is made proportional to the net radiation at the surface. The deep ground temperature flux is estimated using prescribed subsoil temperature at 2.85 m depth as a function of latitude and terrain elevation (Janic 1994). Boundary conditions for the Eta model include SST, snow depth, and orography, which is shown in Fig. 1b.

3. Experimental Design

3.1. The Control Integration

The COLA GCM was integrated for 15 months with atmospheric initial conditions at 00 UTC December 1, 1990, such that two austral summer seasons were covered. The initial condition for the GCM was taken from the NCEP analysis. The observed global SST used during the integration was the NCEP optimum interpolation analysis produced weekly on a 1-degree grid (Reynolds and Smith 1994). The soil moisture and snow cover initial conditions used for the GCM were monthly averaged climatologies from the European Center for Medium-Range and Weather Forecasts (ECMWF) during 1987-1993 on a 1.125 degree grid. These were linearly interpolated to the initial condition day.

The Eta model simulations were made for the austral summer months of December, January, and February 1991/1992, which will be referred to as DJF91/92. The initial condition was taken from the GCM at 00 UTC December 1, 1991. The lateral boundary conditions were taken from GCM simulations at 6-hour intervals.

Before the seasonal integration of the Eta model, a test was performed with a continuous integration during 15 days. The model presented a decrease in precipitable water along time associated with small evaporation rates over the ocean. Therefore, the Eta model seasonal simulation was performed here with re-initializations using the GCM prognostic fields after 30 hours of integration. The re-initialization procedure was also used by Ji and Vernekar (1997) and Berbery and Collini (2000). Its advantages and disadvantages are discussed in Pan et al. (1999). The choice of the 30-hour integration period was based on experiments previously performed with a sequence of 48-hour integrations, in which it was found that the Eta model overestimated precipitation during the first 6 hours due to spin-up (Tanajura et al. 2000). In the present experiment, all first 6-hour Eta model output were neglected, and the seasonal mean was obtained by averaging the last 24 hours of each 30-hour integration. SST and the initial soil moisture and snow depth for the Eta model were the same provided to the GCM.

3.2. The No-Mountain Integration

The no-mountain experiment was performed considering the topography height at sea level over South America for both the COLA GCM and the Eta model. All other boundary conditions, including SST, were kept as close as possible to the run with realistic topography, which will be referred to as the control run.

In no-mountain experiments, there is no standard procedure to set the initial conditions. Previous studies had the models started with the atmosphere at rest (DeWitt 1994; Nigam et al. 1986). Normally, since these types of experiments use low-resolution models and/or run in a perpetual mode, the integrations are performed for long time periods, and a substantial part of the run can be neglected. This was not possible in the present experiment because of the computational costs of the relatively high resolution used in the GCM and in the Eta model. To construct the initial condition for the GCM, NCEP analysis was modified locally only over the mountain regions in South America. The initial condition for the austral summer simulation was chosen on September 15, 1990. The reason for the earlier initial condition in relation to the control run was to allow the GCM atmosphere to adjust to the impact of imbalances in the initial condition fields, as described below. The NCEP fields were available in spectral domain with rhombohedral truncation R40 on 12 pressure levels, and were transformed to the corresponding Gaussian grid. The available horizontal analyzed winds in the 1000, 850 and 700 hPa levels—the three lowest levels in the analysis—were set to zero in the region previously occupied by the Andean mountains. The 1000 hPa winds were also set to zero in central and southeastern Brazil. The second step was to run the GCM in a perpetual day mode for 15 days, so that a redating of the output files would keep all model parameters ‘frozen’ on September 15, 1990. After these 15 days of integration, the values of precipitation and oscillations of eddy kinetic energy and eddy geopotential height reached amplitudes comparable to the ones in the control run. The third step was to integrate the GCM for an additional 75 days until December 1, 1990 to guarantee that the major disturbances caused by the modified initial condition had been dissipated. Finally, the GCM integration was carried on from December 1, 1990 until February 29, 1992. Two summer seasons were simulated, but only the last one was used in the Eta model.

The Eta model no-mountain run was performed during DJF91/92 with the same procedure used in the Eta model control run. The GCM no-mountain output at 00Z December 1, 1991 was used for the Eta model initial condition, and the GCM 6-hour outputs were used as the Eta model lateral boundary conditions. The integrations were done for 30-hour periods, and reinitialized with the no-mountain GCM solutions. The first 6 hours of each 30-hour no-mountain run were also neglected, and a complete time series was formed for DJF91/92 with the last 24 hours of each 30-hour integration.
4. RESULTS AND DISCUSSION

This section compares the mountain and no-mountain runs over the South American region. It focuses on the Eta model results for changes in the precipitation, in the low level convergence, in the SACZ, in the BH, and in the subtropical jet.

4.1. The Precipitation, the Low Level Flow, and the SACZ

Fig. 2 shows the seasonal mean DJF91/92 precipitation produced by the GCM and the Eta model for the control and the no-mountain runs. The observed seasonal mean precipitation according to Xie and Arkin (1996) is shown in Fig. 3, which can be compared with the Eta model and the GCM control runs.

The GCM control run failed to reproduce the precipitation maximum in the central Amazon region, since it placed the maximum over southeast Brazil. The Eta model placed the rainfall maxima deeper inland and produced a precipitation distribution similar to the observed convective cloud distribution discussed in Garreaud and Wallace (1998). They showed the existence of two parallel bands of maximum convective cloudiness over the central and southern parts of the Amazon region, extending from northwest to southeast. The Eta model produced higher rainfall rates than observations in central and southeast Brazil, however the estimated precipitation was produced with relatively low resolution and may not capture the correct spatial variability. The Eta model large-scale pattern and variability are very much dependent on the GCM. In the...
The present experiment, this dependence is enhanced by the re-initialization procedure. Therefore, part of the discrepancies between the Eta model precipitation pattern and observations can be explained by the GCM errors.

The no-mountain run produced a quite distinct precipitation pattern in comparison with the control run. There was an increase of precipitation in equatorial latitudes over northwest South America, and a substantial decrease in the central/southern region (between 15°S and 35°S). This new configuration is strongly linked to changes in the low level circulation and the moisture convergence.

Despite the substantial differences in the precipitation distribution over the continent, the SACZ in the no-mountain case is observed only a few degrees south of the control run position. It is a relatively small displacement, well within the range of the interannual variability of the SACZ (Oliveira 1986). The no-mountain SACZ has its main characteristics unaltered, such as the northwest-southeast orientation and the mean rainfall rate. It is not possible to determine if the shift in the SACZ position is due to the model internal variability or to the topography change. The see-saw pattern (Nogués-Paegle and Mo 1997; Robertson and Mechoso 2000) observed in the circulation and convective activity between the SACZ region, and Argentina, Uruguay, and adjacent areas to the southwest of the SACZ is reproduced by the model in both the mountain and no-mountain integrations.

The mountain/no-mountain experiment indicates that the formation and maintenance of the SACZ do not depend on the orographic forcing of the Andes as substantially as some authors have proposed (e.g. Figueroa et al. 1995; Satyamurty et al. 1980). However, Gan and Rao (1994) have shown that the Andes do influence the propagation of high frequency systems and might be responsible for lee cyclogenesis. The results obtained here indicate that the Andes may slightly influence the location of the SACZ. The relevance of the Andes with respect to the SACZ depends more on their influence on the latent heating distribution than on the orographic forcing itself. This is in agreement with other experiments (Lenters and Cook 1997; Nigam et al. 1986), and is also supported by the presence of the South Pacific Convergence Zone (SPCZ), which is formed in a region far from major mountain complexes. The existence of an intense convective region over the continent, the quasi-stationary subtropical high in the South Atlantic, and the remote forcing from the western Pacific are considered to be the key elements in the SACZ formation (Ko-

![Figure 3](image3.png)

Figure 3: DJF91/92 seasonal mean precipitation according Xie and Arkin (1996). Contour line is 2 mm d⁻¹. Shaded areas are according to gray bar scales of 4, 8, 12 and 16 mm d⁻¹.

![Figure 4](image4.png)

Figure 4: Standard deviation of the Eta model daily mean precipitation with respect to the seasonal mean for (a) the control, and (b) the no-mountain runs. Contour line is 2 mm d⁻¹. Shaded areas are according to gray bar scales of 4, 8, 12 and 16 mm d⁻¹.
The Andes influenced the seasonal mean precipitation pattern as well as the standard deviation of the daily precipitation with respect to the seasonal mean, as shown in Fig. 4 for the control and no-mountain runs. Fig. 4a (control run) agrees qualitatively with Liebmann et al. (1999), who showed that maximum intraseasonal variance of convective activity (estimated by observed outgoing longwave radiation) occurs in the SACZ, and to the south of 15°S over the continent. The variability in the no-mountain run is substantially decreased in Argentina, Paraguay and Uruguay. In the no-mountain case, there is a southward shift of the high variability area associated with the SACZ, and there is a smaller maximum around 15°S.

Fig. 5 shows the 850 hPa seasonal mean wind field and geopotential height for the Eta model control and no-mountain runs. In the control run, important aspects of the climatological circulation were realistically simulated. It includes the circulation of the Pacific and the Atlantic subtropical highs, the easterly flow in the tropical Atlantic that penetrates into South America, and the south-southeastward flow along the eastern side of the Andes. In the no-mountain run, a remarkably different circulation was established. One of the major differences is an east-west flow in the tropics, which comes from the Atlantic, crosses South America and reaches the Eastern Pacific. This pattern has no meridional component over western South America around 20°S, and this substantially affects the moisture advection from the Amazon river basin to the southern regions of the continent.

Fig. 6 shows the seasonal mean total moisture flux (stationary plus transient) at 850 hPa for the control and no-mountain run. The figure also shows the moisture convergence. In both Figs. 6a and 6b there are strong moisture convergence in the tropics. However, there is no southward moisture flow from the Amazon to southern Brazil, Paraguay, Uruguay and Argentina in the no-mountain run, and the lack of moisture convergence contribute to the very low precipitation found in subtropical South America. In these regions and in the southwest Atlantic, the absence of the Andes imposes a much stronger influence of the southeast Pacific Ocean flow.

In the eastern Pacific, the low level circulation and the subtropical high pattern were strongly altered. The no-mountain circulation did not produce the climatological and well-defined northward flow in the subtropics around 80°W, but a zonal flow with meridional shear and very weak meridional component (Figs. 5b and 6b). In the no-mountain case, the South Pacific subtropical high is closer to the continent, and the zonal component of the pressure gradient in the southeastern Pacific is smoother. The flow from the eastern Pacific mid- and high-latitudes, which carries mid-latitude maritime air from the Pacific, reaches the continent and the South Atlantic. The lack of southward flow from the Amazon region and the colder air from the Pacific mid-latitudes lead to colder and drier conditions in southern South America when compared to the control run and to the austral summer climatology. The strength of the South Atlantic subtropical high is also altered in the absence of the Andes, as it is indicated by the mean 850 hPa geopotential fields in Fig. 5. The seasonal mean high becomes stronger. At the same time, the low level moisture convergence region in the southeast Atlantic mid-latitude is intensified, mostly due to the transient component (not shown).

The different low level circulation obtained with and without the Andes suggests the importance of these mountains on the climatological sea surface temperature in regions of the Pacific and Atlantic oceans. The meridional component of the wind off the tropical South American west coast is responsible

Figure 5: Eta model seasonal mean 850 hPa horizontal wind and geopotential height (gpm) for (a) the control run, and (b) the no-mountain run. Reference wind vector is 10 m s⁻¹. Contour interval is 20 gpm.
for two well-known processes that help establishing the equatorial east Pacific. They are: (a) the advection of colder waters from higher latitudes associated with the Peru Current; and (b) the Ekman upwelling (Philander 1990). The wind pattern obtained in the no-mountain run would produce a quite different ocean cold advection and upwelling in the Eastern Pacific and, therefore, quite different sea surface temperature climatology. Also, the change in the low level winds in the southwest Atlantic along the coast of Brazil, Uruguay, and eastern Argentina, off the Plata River region, may induce significant changes in the ocean circulation, such as the confluence zone between the cold Falkland/Malvinas Current and the warm Brazil Current.

The absence of the Andes influenced the propagation of the transient systems in Argentina, Paraguay, Uruguay and southern Brazil. This is in agreement with Gan and Rao (1994). Fig. 7 shows the seasonal mean standard deviation of the 850 hPa meridional wind for the mountain and no-mountain runs. In Fig. 7a, a region with relatively high variability from the east side of the Andes and northern Argentina until the Brazilian shore between 15-30°S could be associated with a representation of the Low Level Jet, the passage of synoptic systems toward southeast Brazil and the formation or intensification of transient systems. This region is not present in Fig. 7b. In the

Figure 6: Eta model seasonal mean 850 hPa moisture flux (kg m kg^{-1} s^{-1}) represented by vectors and moisture convergence represented by shaded areas and contour lines (kg kg^{-1} s^{-1}) for (a) the control run, and (b) the no-mountain run. Reference vector is 0.1 kg m kg^{-1} s^{-1}. Contour interval is 5 x 10^{-8} kg kg^{-1} s^{-1}.

Figure 7: Eta model seasonal mean standard deviation of the 850 hPa meridional wind and for (a) the control run, and (b) the no-mountain run. Contour interval is 1 m s^{-1}.
absence of the Andes, the transient flow decreased intensity in the core of the continent, and contributed to the low precipitation produced in this region.

4.2. The Bolivian High and the Upper Level Circulation

The changes in the circulation between the control and the no-mountain simulations in the upper levels were not as large as in the lower levels, as shown by results with other models (e.g., Figueroa et al. 1995; Gandu and Silva Dias 1998). However, significant changes were obtained. Fig. 8 shows the mean 200 hPa winds and geopotential height produced by the Eta model control and no-mountain runs. One of the main differences between the two runs is the northward displacement of the BH in the absence of the Andes. This is in good agreement with the no-Andes experiment performed by Lenters and Cook (1997) with a GCM. This shift contributed to a more zonal flow in the subtropical region with a less intense subtropical jet. Only the 200 hPa zonal wind component is shown in Fig. 9. The no-mountain sub-tropical jet is about $10^\circ$ to the north of its position in the control run. This change is consistent with a modification of the meridional gradient of temperature in the troposphere. This will be discussed below.

Figure 8: Eta model seasonal mean 200 hPa horizontal wind and geopotential height (gpm) for (a) the control run, and (b) the no-mountain run. Reference wind vector is 10 m s$^{-1}$. Contour intervals are 100 gpm for values below 12400 gpm and 10 gpm above 12400 gpm.

Figure 9: Eta model seasonal mean 200 hPa zonal wind for (a) the control run, and (b) the no-mountain run. Contour interval is 5 m s$^{-1}$.
The 200 hPa geopotential height maxima in the no-mountain run decreased by only about 10 gpm, and showed a well-established BH. The hypothesis by Schwerdtfeger (1976) that the sensible heating from the Bolivian plateau is an important factor to trigger convection and form the BH is not supported by this experiment. The plateau is a vast region of more than 100,000 km² and the control run could represent it with more than 16 grid points. The no-mountain run produced precipitation comparable to the control run over the Amazon region. Therefore, in agreement with other studies (e.g., Nigam et al. 1986; Lenters and Cook 1997), the dynamical processes responsible for deep convection in Amazonia and the formation of the BH in this model experiment did not require the presence of the Andes and/or the Bolivian Plateau. Despite the stronger upper level convergence off Northeast Brazil coast in the no-mountain case (not shown), no important modification on the trough to the east of the BH was observed. This is consistent with the maintenance of dry conditions in Northeast Brazil in the no-mountain case.

The absence of the Andes affected the meridional circulation in the South American sector. Fig. 10 presents the mean meridional circulation (i.e., the stream function for the combined meridional and vertical motions) for the Eta model control run and the difference (no-mountain minus mountain) averaged over the longitude range 40°W-80°W. This figure shows the upward branch of the meridional cell between 20°S and the equator was displaced northward with respect to the control run simulation. The no-mountain run presented equatorward mean flow in the mid-latitudes indicating the penetration of high latitude air masses into the mid-latitudes.

The modification of the meridional gradient of temperature is observed in the whole troposphere, and two explanations on the establishment of different temperature distribution are presented. In the lower troposphere, the change is directly related to the barrier effect imposed by the Andes. It is observed that the Andes separates the low level circulation in the eastern Pacific from the one in the Amazon and central South America regions. There is southerly flow and cold advection on the western side, and northerly flow and warm advection on the eastern side. When the Andes were removed, the low level easterlies in the tropics crossed South America and reached the Pacific. This reduced the meridional cold advection in the east Pacific and the warm advection in western South America. In the mid and upper troposphere, the modifications of the temperature pattern are related to changes in latent heating. It was observed that there was negligible seasonal mean precipitation in the no-mountain run over the southern part of the continent. Thus, changes in the temperature advection in the lower troposphere, and in the latent heating distribution in the mid and upper troposphere contributed to the establishment of a different meridional gradient of temperature. This is discussed in more details below.

The consistency between the changes in the meridional gradient of temperature and the changes in the position of the subtropical jet is supported by Fig. 11. It shows the Eta model seasonal mean temperature in the layer 900-200 hPa, the zonal component of the thermal wind in the layer 900-200 hPa, and the difference of the zonal wind between 200 hPa and 900 hPa. The thermal wind in the layer 900-200 hPa was calculated only up to 5°S to avoid a singularity caused by the vanishing of the Coriolis force at the equator. In the control run, the temperature over the continent had small variations up to 30°S, as seen by the region contained by the 266°K isotherm. The meridional gradient of temperature increased to the south of 30°S. In the no-mountain run, the 266°K isotherm reached only 20°S, and lower temperatures compared to the control run were found in the higher latitudes. The vertical difference of the wind in Figs. 11e and 11f compare extremely well to the thermal wind for both the mountain and no-mountain cases.

A component of the time mean meridional thermal advection in the lower troposphere is presented in Fig. 12. It shows the mean meridional wind multiplied by the meridional derivative of the seasonal mean temperature averaged in the 1000-700 hPa layer for the Eta model control and no-mountain runs. In the control run, warm advection over the continent is observed in the mid-latitudes, and cold advection is found to the west of the Andes in the mid-latitudes and in the tropics. In the absence of the mountains, cold advection dominates the southern part of the continent, showing that the seasonal mean low level meridional wind advected relatively colder air to that region, and that the warmer air from the tropics was unable to reach that region.

Figure 10: Eta model seasonal mean meridional circulation averaged between 40°W-80°W for (a) the control run, and (b) the difference no-mountain minus control. Velocities used to calculate the streamlines are in m/s.
Figure 11: Eta model seasonal mean fields. In the left and right columns, there are fields from the control and no-mountain runs, respectively. The vertically averaged temperatures (K) are displayed in (a) and (b); the zonal thermal winds (m/s) are in (c) and (d); and the vertical zonal wind differences (m/s) between the levels 900 and 200 hPa are in (e) and (f).
4.3. GCM results over the Southern Hemisphere

This subsection describes some results produced by the COLA GCM over the Southern Hemisphere with and without the South American mountains. As mentioned in subsection 3.b, the GCM mountain and no-mountain integrations covered 15 months, which included the two austral summer seasons DJF90/91 and DJF91/92. They were averaged to produce the DJF summer circulation discussed below. The presentation of few GCM results aims to show that the differences between the mountain and no-mountain runs were produced by the change in the surface boundary condition and not by the model internal dynamics.
Figure 14: GCM DJF difference (no-mountain minus mountain) of the 200 hPa (a) zonal wind, and (b) meridional wind for the Southern Hemisphere. The South Pole is in the center of the figures. Contour interval is 2 m s$^{-1}$ (zero line is omitted).

Figure 15: GCM DJF eddy geopotential height along 30$^\circ$S for the control and no-mountain runs in (a) and (b), and along 60$^\circ$S in (c) and (d). Contour interval is 20 gpm.
The GCM mountain and no-mountain results show that the magnitude of the differences between these runs was much larger over the South American sector than away from it. This is a strong indication that the modifications produced over South America were caused by the absence of the mountains and not by the model chaotic component. For instance, Fig. 14 shows the difference (no-mountain minus control) of the mean DJF 200 hPa wind components. Over South America, the differences ranged from -8 to 12 ms\(^{-1}\) in the zonal component and from -8 to 6 ms\(^{-1}\) in the meridional component. Away from the South American sector, the largest differences reached 4 ms\(^{-1}\) in the zonal wind, and 2 ms\(^{-1}\) in the meridional wind.

Because of the northward shift of BH in the no-mountain run, the DJF stationary eddy geopotential height was significantly altered in the tropical South American sector. Fig. 15 shows a cross section of this field along 30\(^\circ\)S and 60\(^\circ\)S for the control and no-mountain runs. Figs. 15a and 15b show the BH around 60\(^0\)W in the control run is replaced by a trough in the no-mountain run. The wavenumber one structure, which explains most of the variance and corresponding fluxes of the quasi-stationary waves in high latitudes of the Southern Hemisphere (van Loon and Jenne, 1972; Quintanar and Mechoso, 1995), is simulated in Figs. 15c and 15d. Note that the GCM simulates the small vertical tilt of the Southern Hemisphere quasi-stationary waves. Again, the magnitude of the differences over South America is larger than away from this region.

The GCM results presented above show that the impact of the absence of the Andes in the South American circulation was mostly concentrated over South America, but some remote effects were produced. In accordance with Kalnay et al. (1986), Nigam et al. (1986) and Lenters and Cook (1997), the influence of the Andes on the organization of the temperature advection and of the latent heat source are more important to the large scale circulation than its role as a topographic source of planetary quasi-stationary waves.

5. SUMMARY

The NCEP Eta model was nested in the COLA GCM to investigate the influence of the Andes on the South American summer climate. The GCM was configured with R40L18 resolution and the Eta model to 80 km in the horizontal domain and 38 vertical levels. The use of a regional model is an attempt to resolve details of the circulation generally not captured by coarser GCMs. The Eta model seasonal simulation was performed with a sequence of 30-hour integrations with outputs provided in 6-hour intervals. The Eta model was re-initialized by the GCM fields, and the first 6-hour simulation of each 30-hour run was neglected, in such a way that a complete time series during DJF91/92 was formed.

The structure of the precipitation produced by the Eta was in better agreement with the observational data than the GCM. However, the Eta model produced maxima much larger than the estimated precipitation. The Eta model showed important spatial variability along the eastern slopes of the Andes, and it captured the rainfall gradient between northeast Brazil and the Amazon region better than the GCM. The maximum precipitation obtained by the GCM was located over southeastern Brazil, and not over the central part of the continent. This indicates that the downscaling technique is able to improve aspects of the climate produced by a GCM over South America as verified in other works (e.g., Chou et al. 2002; Seth and Rojas 2003; Tanajura et al. 2003; Vernekar et al. 2003).

A mountain/no-mountain experiment for the South American region was performed in which the South American topography was removed in both the GCM and Eta model, and other conditions were kept as close as possible to the control run with mountains. The absence of mountains in the present experiment produced major changes in the precipitation and circulation patterns. A new precipitation maximum was formed in southwest South America, over Ecuador, and negligible precipitation was found over the southern half of South America. Over the tropical part of the continent, the precipitation distribution exhibited a more uniform shape with northwest-southeast orientation. However, the precipitation over the Amazon region was still intense and the bulk of the precipitation in the tropical region was not substantially altered. The local maximum close to the eastern shore and the SACZ were present in both the control and no-mountain runs.

In agreement with other studies with complex physics models (Kalnay et al. 1986; Nigam et al. 1986; Figueroa et al. 1995; Lenters and Cook 1997), the SACZ was produced in the absence of the Andes. It was shifted southward, but the precipitation rate and the northwest-southeast pattern were not substantially altered. The difference in the SACZ position with and without the Andes was in the range of the interannual variability. The gross structure of the SACZ has been also reproduced by simpler models with and without topography forced by a prescribed latent heat source (Gandu and Geisler 1991; Figueroa et al. 1995; Gandu and Silva Dias 1998).

In the GCM and Eta model no-mountain runs, the new precipitation maximum produced over Ecuador was associated with a new pattern of low level wind convergence in the equatorial region. It was formed by the convergence of the trade winds from the Northern Hemisphere and the easterlies from the tropical Atlantic, which penetrated the South American west coast.

One of the most important changes produced in the no-mountain run in relation to the control run was the lack of precipitation in the subtropical and southern parts of the continent. It was caused by the lack of southward moisture advection from the Amazon region and by the change in the penetration of mid-latitude synoptic systems. The mean and transient climatological low level southward flow along the eastern flanks of the Andes and adjacent areas (responsible for advecting moisture from the Amazon region to higher latitudes) were not present in the no-mountain run. The new mean circulation in the tropical South America presented a westward flow that crossed the continent and reached the Pacific Ocean. This westward flow completely cut the southward moisture flux. The absence of the Andes also affected the transient synoptic systems from the south, as seen by the reduction of the...
standard deviation of the low level meridional wind in sub-
tropical and mid-latitude regions over the continent.

The South Pacific subtropical high pressure cen-
ter cell was also substantially affected by the absence of
the Andes. The southerly winds in the eastern Pacific lost
intensity because they penetrated into the continent and
reached tropical latitudes. The easterlies from the tropical
Atlantic crossed the continent and reached the Pacific, af-
festing the two subtropical cells in the South Atlantic and
South Pacific in the control run. These results confirm what
is generally accepted: that the Andes are a key factor for
the strong northward flow on their western side, and for the
southward flow on their eastern side. The change in the low
level circulation showed that a new sea surface temperature
climatological front in the southwest Atlantic and equatorial east
Pacific would be established.

The incursion of colder air from the mid-latitude
eastern Pacific into the southern part of the continent,
and the low level easterlies from the tropical Atlantic that
crossed the continent towards the Pacific produced a sub-
stantially different summer in southern South America in
the absence of the Andes. The lack of latent heating in this
region also contributed to form colder air in the mid and
upper levels. The northward shift of the Bolivian High
in the no-mountain simulation with respect to the control run also imposed less mixing of the tropical and mid-lati-
titudinal air masses. Because of the drier and colder condi-
tions in the southern part of the continent obtained in the
no-mountain case, the equivalent potential temperature in
the region was reduced with respect to the control run
(not shown). In the Bolivian region, the reduction reached
11°C at 500 hPa.

Consistent with the precipitation changes between
the mountain and no-mountain cases, the upper level circu-
lation was also affected. The Bolivian High and the South
American upward branch of the meridional cell were dis-
placed north/northwestward with respect to the control run
confirming the strong link between the latent heating distri-
bution and the Bolivian High. The subtropical jet was also
shifted northward, in agreement with changes in the meridi-
onal gradient of temperature.

The mountain/no-mountain GCM results in the
Southern Hemisphere showed that the largest differences
in the upper level circulation were obtained in the South
American sector. The stationary eddy in the subtropics and
in the high latitudes were influenced by the changes in the
position of the BH and in the low level circulation. How-
ever, the magnitude of the changes were higher over South
America. As suggested by earlier studies (e.g., Nigam et
al. 1986; Kalnay et al. 1986; Lenters and Cook 1997), the
Andes are more important to the general circulation in the
Southern Hemisphere because of their effects on the low
level convergence, precipitation, and associated latent heat
of condensation than because of their role as a topographic
source of quasi-stationary waves.

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