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The influence of the Andes mountains on the South American low-level flow

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[1] A dry, hydrostatic, three-dimensional primitive equation model is used to evaluate the mechanical effect of the Andes mountains on the South American low-level flow (LLF). The model simulations reproduce the evolution of a baroclinic wave over the continent under winter and summer conditions. In both seasons as a consequence of the interaction between the basic flow and the Andes, northerly LLF was reproduced east of the Andes which resembles the main characteristics of the observed flow. Moreover, seasonal changes of cyclone activity have a significant impact on the location of maximum LLF and its alignment, which exhibits a NW-SE orientation during winter and more meridional orientation in the warm season. *INDEX TERMS:* 3367 Meteorology and Atmospheric Dynamics: Theoretical modeling; 3364 Meteorology and Atmospheric Dynamics: Synoptic-scale meteorology; 3399 Meteorology and Atmospheric Dynamics: General or miscellaneous. **Citation:** Campetella, C. M., and C. S. Vera, The influence of the Andes mountains on the South American low-level flow, *Geophys. Res. Lett.*, *29*(17), 1826, doi:10.1029/2002GL015451, 2002.

1. Introduction

[2] The low-level circulation over South America promotes a strong exchange of heat, moisture, aerosols, etc. between the tropics and extratropics throughout the year. The seasonal mean low-level winds computed from the European Centre for Medium Range Forecast (ECMWF) reanalysis dataset (Figure 1) shows easterly trades penetrating into tropical South America from the equatorial Atlantic. Due to the presence of orography, the low-level winds are then deflected to the south and channeled along the Andes eastern slope. Near the Andes "elbow" (at around 20°S where the Andes significantly change their orientation) the winds achieve a maximum, with frequent low-level jet episodes [*Salio et al.*, 2002, and references therein].

[3] It is well known that tropical South American climate is of a monsoonal-type nature with a distinctive rainy warm season. However, the seasonal cycle of the low-level winds is not very large, being the winter flow slightly stronger and with a narrower vertical structure than that during summer (Figures 1c and 1d). *Nogués-Paegle et al.* [1998] suggest that the distinctive Andes features may be responsible for the small seasonal variation of the low-level flow (LLF). The Andes extend from equatorial latitudes to high latitudes, on the other hand they exhibit mesoscale dimensions on the order of 500 km or less in the east-west direction. As a consequence, the lower-tropospheric circulation might be approximated by simple, adiabatic models in which orography provides only mechanical, rather than diabatic heating modifications of the zonally averaged circulation [*Byerle and Paegle*, 2002].

[4] Efforts to model the South American low-level circulation have mostly concentrated on the summer circulation and generally have employed simply numerical models with poor representation of the Andes [*DeMaria*, 1985; *Silva Dias et al.*, 1987; *Kleeman*, 1989; among others]. *Figueroa et al.* [1995], using a multilevel limited-area primitive-equation model, simulated the effects of both the Amazonian latent heat source and the Andes on the South American summer circulation. They reproduced the main features of the mean summer circulation although the southern penetration of LLF east of the Andes was not well represented, probably due to the coarse model resolution considered.

[5] The present study is distinguished from the previous works as it tries to explain what controls the South American LLF by studying the dynamics of the interaction between the westerly mean-flow and the Andes. We hypothesize that, in the absence of diabatic heating and moist physics, the topographic forcing is sufficient to reproduce the main observed features of the South American LLF.

[6] The Andes mountains produce a strong modulation in the propagation and evolution of synoptic-scale waves over southern South America [*Gan and Rao*, 1994, among others]. Recently, *Vera et al.* [2002] and *Vera and Vigliarolo* [2000], using reanalysis data, have shown that cyclonic baroclinic perturbations play a key role enhancing the poleward flow penetration and favoring precipitation. Thus, a number of numerical integrations of a dry hydrostatic primitive equation model simulating the evolution of a baroclinic cyclonic system over South America are presented here. We will show that the cyclone strengthening on the lee side of the Andes controls the occasional southward penetration of the LLF into subtropical regions.

2. The Numerical Model

[7] A hydrostatic, dry, three-dimensional primitive equation model based on the anelastic Boussinesq approximation is employed *Solman* [1995]. The coordinates are latitude, longitude and the geometrical height (z). Frictional effects are included as well as a second order diffusion term to damp subgrid-scale noise. No other physical processes are included. The integration domain is hemispheric between the Equator and 75°S with a horizontal resolution of 1.5° × 1.5° and 16 vertical levels with high resolution at lower levels (10 levels in the lowest 5500 m). The boundary conditions are cyclic in the west-east direction, imperme-

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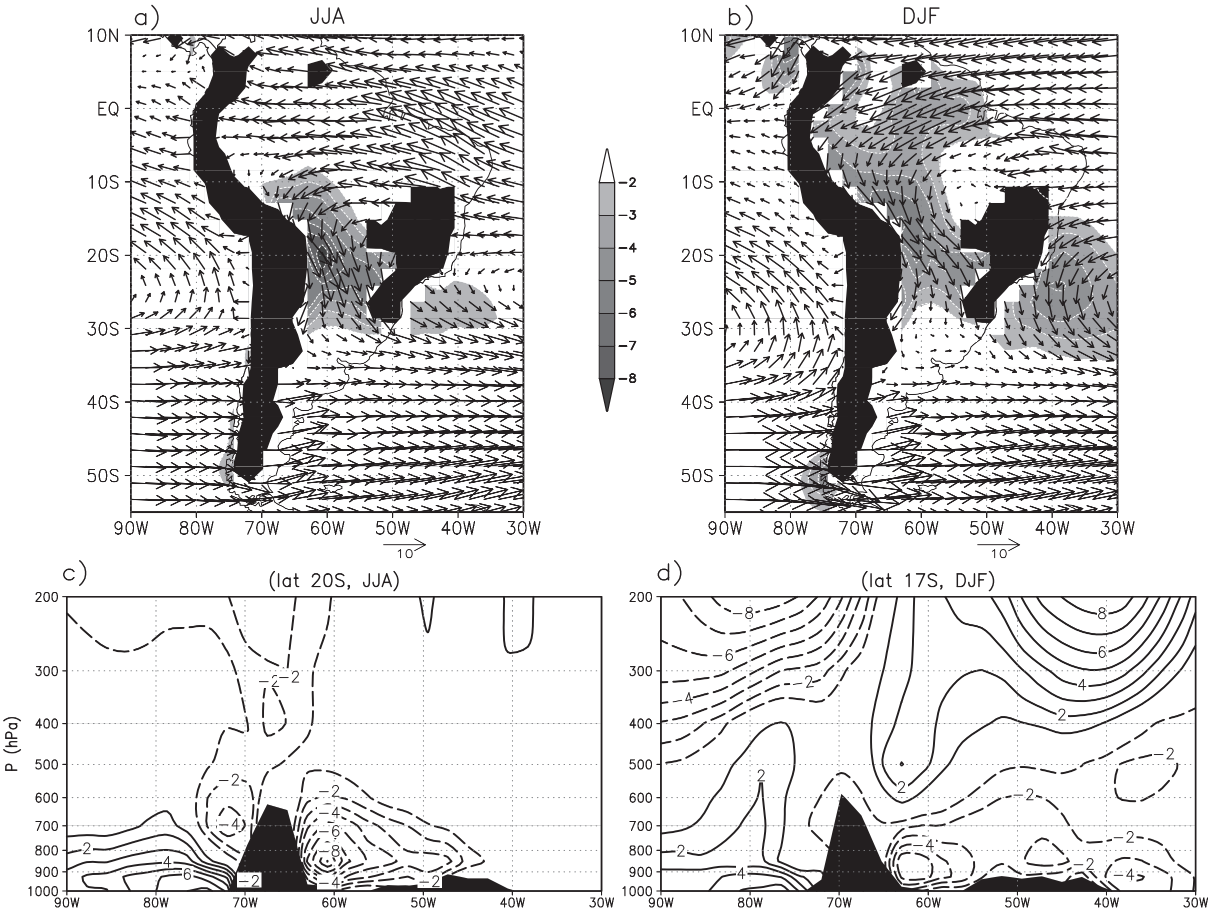

Figure 1. (a) Mean horizontal wind field (vector) and mean meridional wind at 850 hPa (shaded) averaged from June through August 1979–1993. Contour interval is 2 m s^{-1} and values lesser than −2 m s^{-1} are shaded. Orography higher than 700 m is black colored. (b) as in (a) but averaged from December through February. (c) longitude-height section of the JJA mean meridional wind at 20°S. Contour interval is 1 m s^{-1}, negative contours are dashed and zero contour is omitted. (d) as in (c) but for the DJF meridional wind at 17°S.

able walls are set at the north and south limits and a rigid lid is set as the upper boundary condition at 15 km.

3. Description of the Simulations

[8] The simulations presented here encompass two consecutive integrations:

Integration A: a localized barotropic vorticity perturbation of small amplitude is superimposed on a zonally symmetric jet with a vertical structure similar to that observed over the southwestern Pacific [*Simmons and Hoskins*, 1979; *Orlanski and Chang*, 1993] and allowed to grow over flat terrain. After 8 days of integration, the perturbation evolved into a mature baroclinic wave (Figure 2).

Integration B: the mature baroclinic perturbation is isolated by subtracting its zonal mean, and superimposed on a zonally symmetric jet, resembling that observed over the South American region. A 10-day integration including the Andes is then performed being the perturbation initially located 15° upstream the Andes. That integration length is long enough to reproduce the evolution of the system over South America.

[9] In the next section, results of two simulations reproducing austral winter and summer circulation are discussed. The winter mean zonal wind at upper levels is characterized by the presence of a very strong subtropical jet along 30°S with maximum intensity over Australia, and a secondary jet over the southern Indian Ocean at around 50°S (see Figure 1a of *Berbery and Vera* [1996]). Two regions of high baroclinicity associated with the double jet structure are observed in the vicinity of South America, which favor the development of synoptic-scale waves [*Vera et al.*, 2002]. In this paper the winter simulation resembles the evolution of the synoptic waves along the subtropical jet latitudes, as they are the most strongly modified by the presence of the Andes. On the other hand, the basic state in the summer simulation is characterized by a single jet located at around 50°S, which is a typical feature of the observed summer mean zonal wind [*Vera and Vigliarolo*, 2000].

4. Simulation Results

[10] The numerical simulation for austral winter conditions reproduces the evolution of a cyclonic perturbation that moves along 35°S eastward from the eastern South Pacific, taking around 6 days to cross South America. While the upper-level perturbations are mostly unaffected by the presence of the Andes, the low-level cyclone surrounds the

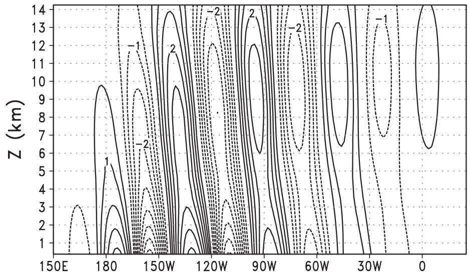

Figure 2. Longitude-height section at 35°S of the meridional wind at day 8 of *integration A* for austral winter conditions (see section 3 for integration details). Contour interval is 0.5 m s^{-1}, negative contours are dashed and zero contour is omitted.

Andes between 35°S–45°S while migrating equatorward on the lee (figures not shown). That detachment between the upper and lower portion of the perturbation produces a weaker eddy baroclinic growth and thus weakens the low-level cyclone. Once the upper-level cyclone is on the lee side, the perturbation acquires a more typical baroclinic wave structure and low-level intensification of the system occurs around 1000 km east of the orography. The modifications suffered by the cyclone in its path across the Andes are well known in the region and the simulation results presented here well agree with those by *Vera et al.* [2002] who performed a climatological study of those cyclones and also with those by *Seluchi and Saulo* [1998] who extensively studied individual cyclogenesis events over that area.

[11] By day 5 of integration B (described in section 3), the LLF attains its maximum intensity at subtropical latitudes (Figure 3a). The simulated flow exhibits the typical NW-SE orientation characteristic of the observed mean winter LLF (Figure 1a). However, the simulation shows that the evolving cyclone provides favorable conditions for an anomalous southward flow penetration until 37°S in agreement with observed cases of cyclonic development (Figure 7b of *Vera et. al.* [2002]). Because the highlands located on the southeastern coast of Brazil were not included in the model topography, thus the LLF is not as channeled as is the observed (Figure 1a). The location of the low-level meridional wind maximum at around 20°S and the corresponding meridional-wind vertical structure are also well captured by the model (see Figure 1b and Figure 8a of *Vera et al.* [2002]). The vertical cross-section displayed in Figure 3c shows evidence of the upper-level synoptic wave with a secondary maximum of northerly winds at around 12 km.

[12] Further analysis reveals that the LLF penetration enhances warm air advection east of the cyclone center contributing to its intensification and in turn to the southward LLF maintenance. Although moist processes are not considered in this model, it should be pointed out that the observed southward flow also enhances moisture transport from tropical latitudes along the eastern portion of the low-level cyclone, favoring both precipitation occurrence over southeastern South America and consequently a cyclone strength-

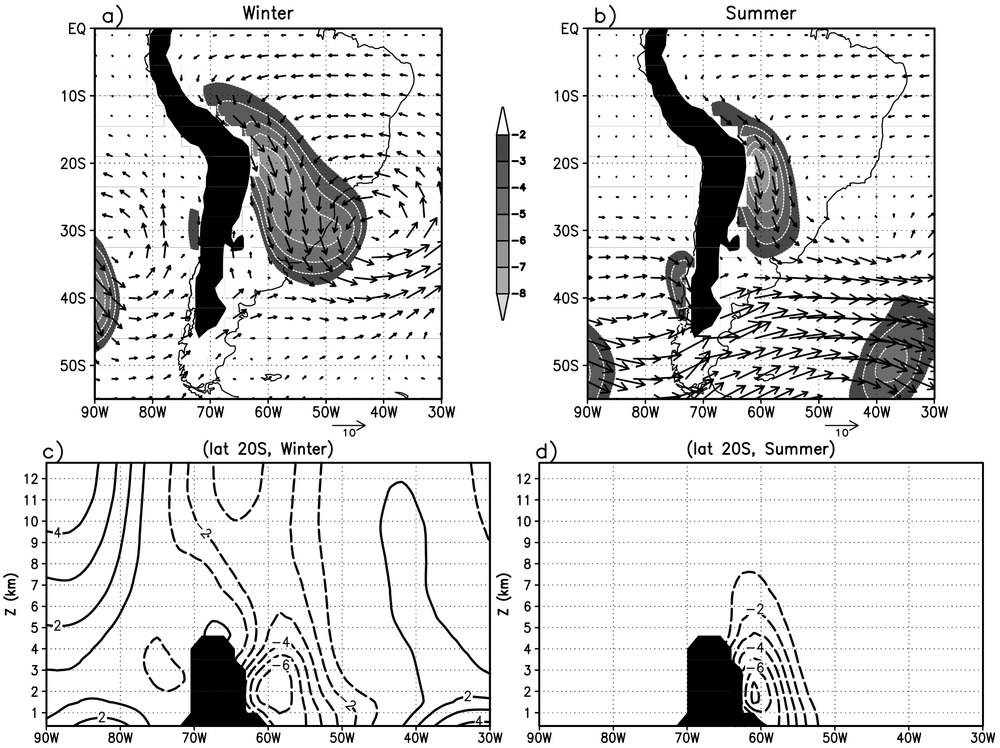

Figure 3. (a) Horizontal wind field (vector) and meridional wind at 1500 m (shaded), for day 5 of *integration B* for winter simulation. Contour interval is 2 m s^{-1} and values lesser than -2 m s^{-1} are shaded, (b) as in a) for day 4 of *integration B* for summer simulation. Model orography higher than 1000 m is black colored. (c) longitude-height section of the meridional wind for day 5 of 5 of *integration B* for winter simulation at 20°S. Contour interval is 1 m s^{-1}, negative contours are dashed and zero contour is omitted. (d) as in c) at day 4 of 5 of *integration B* for summer simulation.

ening due to diabatic heating release [*Vera et al.*, 2002]. The simulated LLF weakens during the following days as the decaying cyclone moves eastward (figures not shown).

[13] During summer the main baroclinic region is located further south at around 50°S. As a consequence, paths of eastward propagating synoptic-waves are located poleward of the highest elevations of the Andes and only their equatorward flanks are disturbed by the orography [*Vera and Vigliarolo*, 2000]. The integration B for summer conditions shows the development of the southward LLF on the eastern slope of the Andes from the first day of the simulation when the low-level cyclone is located on the southwestern tip of South America (not shown). By day 4 (Figure 3b) the system has moved off the eastern coast of South America and the LLF displays its maximum strength at around 20°S that is south of its observed climatological position (Figure 1b). A comparison with winter simulation shows that the southward flow penetration produced by the summer cyclone is not as intense as that associated with the winter system (Figures 3a and 3b).

[14] The modeled summer vertical flow shows a core at tropical latitudes concentrated along the eastern slope without evidence of a synoptic-type structure aloft and without evidence of the monsoonal-type vertical structure present in the observed mean meridional flow (Figure 1d). The fact that this model does not include diabatic heating forcing may explain such differences [*Figueroa et al.*, 1995]. However, the main features of the simulated summer circulation, such as the location of the low-level wind maximum and the southward direction of the flow, agree well with those observed by *Salio et al.* [2002] as characteristics of the more intense low-level jet cases.

5. Conclusions

[15] Simulations of the atmospheric circulation over South America only forced by the Andes reproduce the main features of the low-level winds. Moreover, neither diabatic heating nor moist physics were necessary to explain the leading dynamical characteristics of the observed flow as it was hypothesized. In particular, the low-level northerly flow east of the Andes has clearly emerged from the interaction of the basic flow and the Andes.

[16] Simulations show that the evolution of synoptic-scale waves over South America produces a strong modulation of the LLF in agreement with other works based on observational diagnostics and case studies. Seasonal changes of cyclone activity have a significant impact on the LLF maximum location and orientation. During winter, the presence of the subtropical jet allows the development of intense cyclones over subtropical South America, promoting at the lee intensification of low-level winds with NW-SE orientation. On the other hand, during summer the basic flow and the cyclone activity move further south at around 50°S, forcing a LLF with a noticeable N-S orientation.

[17] Although the LLF three-dimensional structure resembles that observed during low-level jet episodes, the simulated flow intensity is weaker, as observed low-level jet events exhibit typical wind speeds of around 15 m s^{-1} [*Salio et al.*, 2002]. The fact that the model resolution used here is not high enough to reproduce the mesoscale features of the Andes might explain that result. Also, low-level jet events have a strong diurnal cycle that is not reproduced by the simulations. Although this diurnal variation seems to be related with diabatic forcing, the mechanisms underlying the occasional low-level flow strengthening are not clear yet. For these reasons, the Variability of American MOnsoon Systems (VAMOS) Panel in the CLImate VARiability (CLIVAR) component of the World Climate Research Program (WCRP) has implemented the South American Low-Level Jet experiment (SALLJEX) that is an internationally coordinated effort to monitor, quantify, and analyze the low-level circulation over South America (http://www.clivar.org/organization/vamos/index.htm) with a field campaign currently planned for the austral summer of 2002–2003. As a consequence, further simulations based on SALLJEX results are planned in order to explore the role of the diabatic heating forcing on the southward LLF over South America.

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