P2.24 DESCRIPTION OF THE SEASONAL CYCLE OF LOW-LEVEL FLOWS FLANKING THE ANDES AND THEIR INTERANNUAL VARIABILITY

Lee A. Byerle* and Jan Paegle
University of Utah, Salt Lake City, Utah

1. OVERVIEW

Long term fluctuations in low-level circulations east of the Andes appear tied to several mechanisms. Some of these may be from remote influences, such as ENSO, while others may relate to long term changes of local surface processes such as evapotranspiration. This study aims to quantify the variability of low-level circulations surrounding the Andes through diagnostics of monthly-averaged NCEP-NCAR reanalyses and numerical simulations using the Utah Global Model. The region of the Andes has a strong monsoonal signature in the warm season, including a pronounced vertical flow reversal. This monsoonal characteristic is much more pronounced over South America than most of North America, and it appears to contribute to the active low-level jets observed east of the Andes during the warm seasons. The Andes tend to produce an orographically-bound cyclone in winter, with poleward low-level flow located to the east of the mountains. We address here the climatological signal, interannual variability, and possible dynamical mechanisms associated with flow across the Andes.

2. CLIMATOLOGY OF THE SEASONAL CYCLE

Fig. 1a and 1b display December to February (DJF) and June to August (JJA) 700 mb eddy geopotential winds and heights using the 47-year average (1953-1999) of the NCEP-NCAR monthly reanalysis data set. The zonal average has been extracted to emphasize the seasonal cycle and to allow a clearer picture of longitudinal phasings. Cyclonic rotation in both seasons is evident at subtropical latitudes, centered just west of the Andes mountains. The summer pattern at 200 mb (not shown) contains an anticyclone over subtropical south America from approximately 15°S to 35°S, sometimes referred to as the "Bolivian High." In winter, the upper-level pattern (not shown) exhibits cyclonic rotation over South America. Whereas the winter-to-summer transitions are pronounced aloft, the circulation at 700 mb does not change significantly from summer to winter (compare Fig. 1a and 1b). This is evident in the 700 mb eddy vorticity fields shown in Fig. 2a and 2b for summer and winter, respectively. Negative (cyclonic) vorticity flanks the Andes in both seasons and the centers of vorticity are slightly stronger in winter. A significant low-level thermal ridge is evident in the vicinity of the Andes during summer (not shown). Zhou and Lau (1998) suggest the summer surface low results mainly from intense sensible heating associated with increased solar energy over the Bolivian plateau. Although the summer lower troposphere cyclone may have some relation to the strongly heated Andes slopes in that season, alternative mechanisms must be sought for the winter cyclones there which do not have a pronounced warm core. We address this question in section 4.

*Corresponding author address: Lee A. Byerle, Univ. of Utah, Dept. Of Meteorology, Salt Lake City, UT 84112; e-mail: labyerle@met.utah.edu

3. INTERANNUAL VARIABILITY

The climatological average is significantly perturbed in individual years. To illustrate this we emphasize atmospheric features contributing to the water budget and precipitation over South America. One of the key atmospheric features is a northwesterly low-level jet (LLJ) that is commonly situated east of the Andes mountains and transports atmospheric moisture from the humid Amazon rain forest toward the fertile plains of subtropical South America (e.g. Nogués-Paegle and Mo 1997). The east Andean LLJ is evident both in summer and winter in the 700 mb eddy fields of Fig. 1a and 1b. It is particularly pronounced over Bolivia, extending southeastward across Paraguay and southeast Brazil, including portions of the La Plata river basin.

Figs. 3a and 3b present winter and summer temporal correlations of the local 700 mb wind with the 200 mb zonal flow. The 200 mb zonal flow is averaged over the indicated box centered above the Andes and extends from 20°S to 40°S. The eastward/northward component of the vectors denotes the magnitude of the correlation coefficient between the area-averaged upper tropospheric zonal wind within the box against the local zonal/meridional flow component at 700 mb. Stronger upper tropospheric, subtropical westerlies correlate with increased lower tropospheric, cyclonic rotation within the boxed region. In addition, they correlate with stronger northwesterly winds emanating from the Amazon basin that flow toward the La Plata River basin of southeast Brazil, Paraguay, Uruguay and northern Argentina. The cyclonic tendency in the vicinity of the Andes is present in both seasons, though more definitive during summer (Fig. 3a). The results suggest a potential for enhanced inter-basin moisture transport from the Amazon to the La Plata basin in the presence of relatively strong subtropical, upper tropospheric jets over the Andes mountains. Correlations of vertically integrated moisture flux with the 200 mb zonal flow are not presented here, but they show results similar to Fig. 3.

The enhanced atmospheric moisture flux from the Amazon basin contributes to heavier precipitation over the La Plata basin. This connection can be illustrated with the pointwise, 47-year (1953-1999) correlation of 200 mb cross-Andes zonal flow with regional precipitation, displayed in Fig. 4. The largest correlation coefficient (above 0.4) is centered on the La Plata basin. It is statistically significant at the 95% level.

4. DYNAMICAL INTERPRETATION

We consider three processes that may influence monsoonal circulations in the vicinity of high orography. These are enumerated below:

i) Dynamical, mechanical effect of orographic blocking;
ii) Thermal effect of surface heating of an elevated surface;
iii) Thermal effect of latent heating on elevated slopes.

Direct effects of surface heating (mechanism ii) of an elevated plateau generate upslope, buoyancy-driven circulations. The convergence of such slope-driven flow toward the highest mountains would produce cyclonic rotation in the vicinity of the orography (e.g. Gutzler and Preston 1997, and Zhou and Lau 1998). The lower tropospheric cyclonic flows found in the vicinity of the Andes in Fig. 1a and 1b are qualitatively consistent with this mechanism, but the seasonal transitions are not. If this were the dominant mechanism, the cyclonic circulation would decrease from summer to winter as surface heating diminishes. Although a warming effect of the plateau reduces from summer to winter (not shown), the cyclonic vorticity does not decrease (compare Fig. 2a with Fig. 2b), but instead shows some increase in the colder season.

Thermal effects of latent heating on elevated slopes (mechanism iii) would also produce lower-tropospheric cyclonic rotation in the vicinity of rainy slopes. Because latent heating is commonly distributed through a deep tropospheric layer, upward motion associated with latent heat of condensation usually extends vertically through much of the troposphere and produces divergence in the upper troposphere. The divergence would generate anticyclonic rotation in the upper troposphere. This mechanism has been used to explain the upper-level Bolivian High during summer. The summer pattern of Fig. 1a displays cyclonic rotation in the lower troposphere. A vertical monsoonal circulation reversal, with anticyclonic flow aloft, also characterizes the summer conditions of both South America and South Asia.

Mechanim (iii), however, does not explain the circulations situated in the vicinity of the Andes during winter, where flow at the surface (Fig. 1b) and aloft (not shown) are cyclonic. Additionally, it does not directly explain the correlation of upper tropospheric zonal wind with lower tropospheric cyclonic vorticity in both winter and summer. The zonal flow correlations with precipitation (Fig. 4) show regions of both increased and decreased precipitation over the Andes during episodes of stronger westerly flow, and there is no evidence of systematically increased latent heating with stronger westerly flow over the high Andes. The dynamical, mechanical effect of orographic blocking (mechanism i), based on simple barotropic theory, is a third possible explanation to the observed circulations in the vicinity of the Andes. It is based on the barotropic vorticity equation, applied with a beta plane approximation to a one layer atmosphere above idealized orography. The solution to the barotropic vorticity equation has been noted by Charney and DeVore (1979) and Nogués-Paegle (1979), in which an anticyclone is found over the mountains in the presence of strong zonal flow, and a cyclone is predicted for weak zonal flow over orography. The next subsection addresses flow oscillations associated with barotropic theory and orography.

5. BAROTROPIC THEORY AND PRIMITIVE EQUATION SIMULATIONS

The phase speed, C, of Rossby waves in a non-divergent, single-layer barotropic fluid is:

$$C = (U - \beta / k^2); \qquad (1)$$

where U is the uniform, zonal background flow, k is horizontal wavenumber, and ß is the meridional gradient of the Coriolis parameter, assumed constant for a “beta-plane” approximation. For a quasi-stationary seasonal response, C = 0, and “super-critical” conditions exist when $(U - \beta / k^2)$ is greater than zero; “sub-critical” conditions exist when $(U - \beta / k^2)$ is less than zero; and resonance occurs when $(U - \beta / k^2)$ is equal to zero. For the steady response, “super-critical” conditions produce an anticyclone over the mountains when the zonal flow is sufficiently strong; and sub-critical conditions produce a cyclone over the mountains for weaker westerly flow.

The observed correlations over the Andes suggest subcritical conditions, or a low-level cyclone over the mountains, in both winter and summer. To more clearly support or refute the relevance of the barotropic mechanism and its applicability to prediction, we present results from ongoing research using an adiabatic, 20-level, primitive equation version of the Utah Global Model, truncated at wavenumber 42, with 2° nodal spacing in latitude. The zonally averaged portion of the circulation is maintained at the reanalysis value by rapid relaxation of the flow field toward the climatology for each month. The simulations (Fig. 5) retain a full and realistic spectrum of orography and ambient flows. Figs. 5a and 5b represent the difference in wind vectors (m/s) between the simulations with and without orography. An orographically bound cyclone over the Andes is apparent for both January and July conditions. This result is similar to Fig. 13 of Nogués-Paegle et al. (1998), but suggests an even stronger mechanical signal, evidently due to the higher resolution of present integrations. The results support an important role for mechanical flow blocking in the seasonal cycle, and possibly for interannual variability associated with changes of zonal index in relation to near-resonant conditions.

Acknowledgements. This research was supported by NSF grant ATM0106776 to the University of Utah. The first author's participation in this research is also supported by the USAF, and we have benefitted in discussions with J. Nogués Paegle.

REFERENCES

Charney, J.G., and J. Devore, 1979: Multiple flow equilibria in the atmosphere and blocking. *J. Atmos. Sci.*, **36**, 1205-1216.

Chen, M., P. Xie, J.E. Janowiak, and P.A. Arkin, 2002: Global land precipitation: a 50-year monthly analysis based on gauge observations. *J. Hydrometeor.*, in press.

Gutzler, D.S., and J.W. Preston, 1997: Evidence for a relationship between spring snow cover in North America and summer rainfall in New Mexico. *Geophys. Res. Lett.*, **24**, 2207-2210.

Nogués-Paegle, J., 1979: The effect of topography on a Rossby wave. *J. Atmos. Sci.*, **36**, 2267-2271.

_____, and K.C. Mo, 1997: Alternating wet and dry conditions over South America during summer. *Mon. Wea. Rev.*, **125**, 279-291.

_____, K.C. Mo, and J. Paegle, 1998: Predictability of the NCEP-NCAR Reanalysis model during austral summer. *Mon. Wea. Rev.*, **126**, 3135-3152.

Zhou, J., and K.-M. Lau, 1998: Does a monsoon climate exist over South America? *J. Climate*, **11**, 1020-1040.

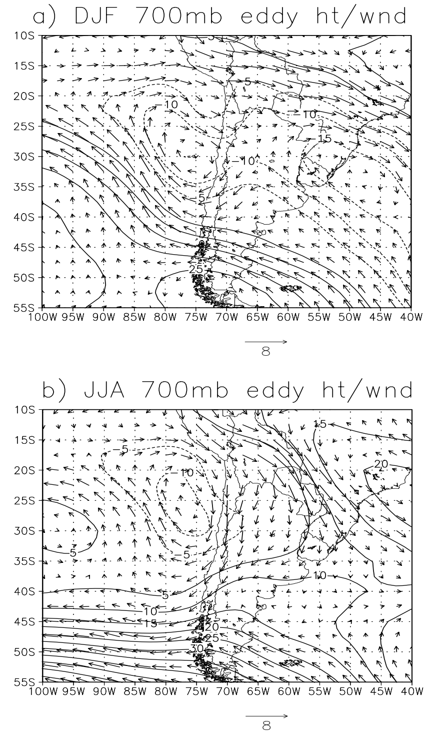

Fig. 1. 700 mb eddy heights (m) and vector winds (m/s) for (a) DJF and (b) JJA (1953-99). Solid contours are positive, dashed contours are negative.

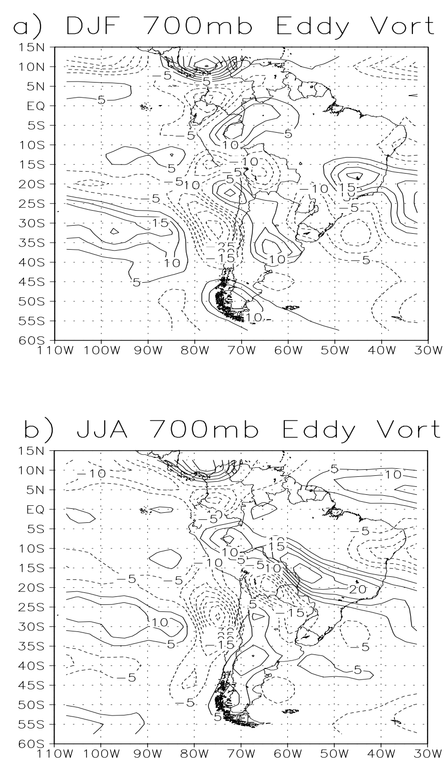

*Fig. 2. 700 mb eddy vorticity (*3E+06/s) for (a) DJF and (b) JJA (1953-1999). Dashed contours indicate cyclonic, solid contours indicate anticyclonic vorticity.*

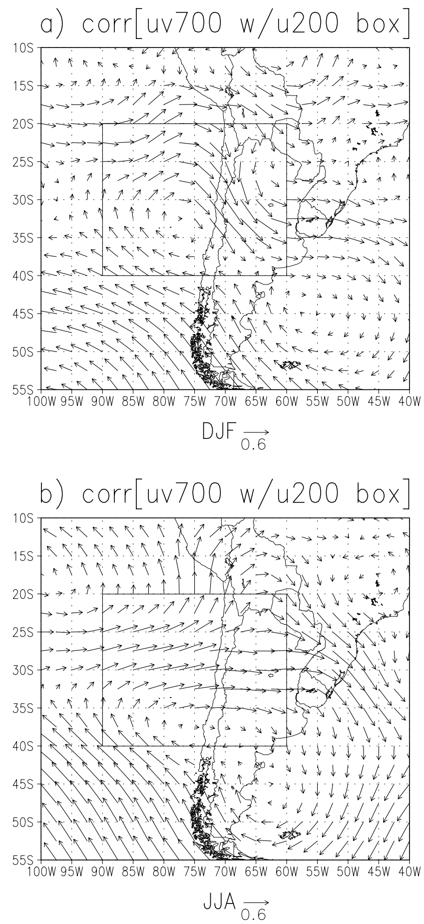

Fig. 3. Temporal correlation of 700 mb wind at all locations with area-averaged 200 mb zonal flow in the region indicated by the box for (a) DJF and (b) JJA (1953-99). Vectors denote magnitude of correlation coefficients.

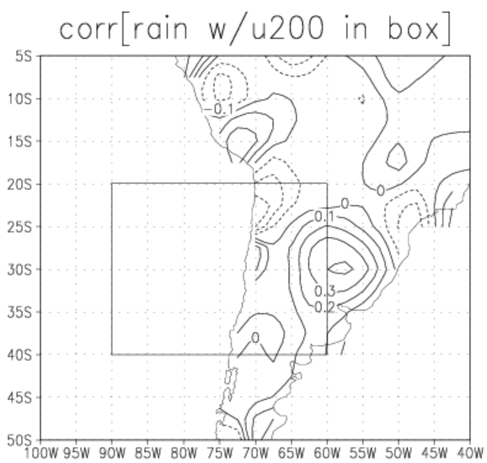

Fig. 4. Temporal correlation of gauge precipitation at all locations with area-averaged 200 mb zonal flow in the region indicated by the box for (a) DJF and (b) JJA (1953-99). The precipitation data are from the Precipitation Reconstruction Climatology over Land (PREC/L) of Chen et al. (2002). Solid contours are positive, dashed contours are negative coefficients.

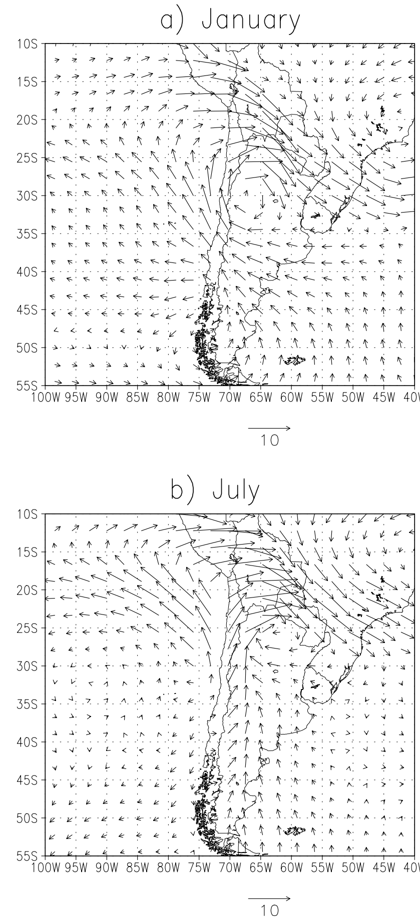

Fig. 5. Orographic effect for sigma level .78 of a 20-level, adiabatic, primitive equations model truncated at wave number 42 for (a) January and (b) July. The figures represent the difference in wind vectors between simulations with and without the Andes mountains.