Influence of Cross-Andes Flow on the South American Low-Level Jet

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ABSTRACT

By analyzing the 15-yr (1979–93) reanalysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF), it has been found that the seasonal and synoptic time-scale variations of the South American low-level jets (LLJs) are largely controlled by an upper-level trough and associated low-level zonal flow, rather than by horizontal temperature gradients along the slope of the Andes. The northerly LLJs are maintained by strong zonal pressure gradients caused by the upstream trough and westerly flow crossing the Andes through lee cyclogenesis. The process involves both baroclinic development of the upper-level trough and mechanical deflection of the westerly flow by the Andes. When an anticyclonic circulation replaces the trough and westerly flow over the eastern South Pacific, the northerly LLJs tend to diminish or reverse into southerly LLJs. The dependence of the LLJs upon the upstream wind pattern helps to explain how the seasonal variation of the South American LLJs is related to the seasonal changes of the large-scale circulation pattern over the eastern South Pacific. On synoptic time scales, the relation between LLJs and cross-Andes zonal flow is strong in austral winter, spring, and fall. This relation weakens somewhat in summer, when Amazon convection is strongest. The analysis also demonstrated strong connections of the LLJs with South American precipitation, intensity of the South Atlantic convergence zone (SACZ), and low-level cross-equatorial flow. A method for up to 5-day forecasts of the LLJs based on 700-hPa zonal winds over the subtropical eastern South Pacific was also introduced. A cross validation indicates a certain degree of predictability for South American LLJs. The results further suggest that the upstream flow pattern over the South Pacific should be closely monitored to determine the variability of the South American LLJs.

1. Introduction

The South American low-level jet (LLJ) is located to the east of the Andes in the subtropics. The LLJs play an important role in regional climate. They transport water vapor from the Amazon basin to central South America (Berri and Inzunza 1993; Nogues-Paegle and Mo 1997; Li and Treut 1999; Berbery and Collini 2000; Berbery and Barros 2002). They are also closely related to mesoscale convective complexes over the La Plata river basin and nocturnal rainfall (Velasco and Fritsch 1987; Stensrud 1996). Hence, the South American LLJ is believed to be a main supplier of water vapor for precipitation over the La Plata river basin. This area is home to about 50% of the combined population of Argentina, Bolivia, Brazil, Paraguay, and Uruguay, and produces about 70% of the total gross national product (GNP) of the five countries. Due to lack of observations, however, the LLJs in South America are among the least understood. Paegle (1998) has summarized some observed features, including a deep vertical structure and late-afternoon wind maxima (Berri and Inzunza 1993; Douglas et al. 1998). As Paegle (1998) noted, the spatial and temporal variations of South American LLJs and their controlling mechanisms remain very much unknown.

North American LLJs over the Great Plains, however, have been much more thoroughly studied for several decades (e.g., Bonner 1968; McCorcle 1988; Savijarvi 1991). Stensrud (1996) presented a comprehensive review of mechanisms responsible for the LLJ formation, such as nocturnal decoupling between the planetary boundary layer (PBL) and the surface layer (Blackadar 1957), thermal winds induced by horizontal temperature gradients over the eastern slopes of the Rocky Mountains (e.g., Holton 1967; Bonner and Paegle 1970), and the effect of upper-level jet streams and lee cyclogenesis (Uccellini 1980). The LLJs have also been shown to be a main moisture provider for summer precipitation over the central United States (Helfand and Schubert 1995; Higgins et al. 1997). However, with some limited available wind profiles, Paegle (1998) suggested that the aforementioned theories cannot explain some of the very important behaviors of the South American LLJs.

The North American LLJs over the eastern slopes of the Rockies occur mainly during summer (Stensrud 1996). In contrast, the LLJs in South America appear to the east of the Andes throughout the year, though

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they are strongest in austral winter (Li and Treut 1999; Nogues-Paegle et al. 2002). These differences in seasonality suggest that different processes may control the seasonal changes of the LLJs over the two continents. Clearly, both North and South American LLJs are mesoscale systems related to topography. To some extent, both the Andes and the Rockies have the same orientation and elongate from Tropics to high latitudes. This similarity may lead to a speculation that the South American LLJs are simply a counterpart of the North American Great Plains LLJs. There are, however, some distinctions between the two mountain ranges (Nogues-Paegle and Paegle 2000; Marengo et al. 2002). The Andes are higher than the Rockies, but much narrower in zonal dimension. The slope of the Andes is thus much steeper than that of the Rockies. In addition, strong convections and associated latent heat over the Amazon and the Altiplano are an important heat source for the subtropical circulation (Silva Dias et al. 1983; Figueroa et al. 1995; Garreaud 1999; Garreaud and Aceituno 2001) and hence for the South American LLJs. How these distinctions may cause different regional circulation response to topography and how the mechanisms responsible for South American LLJs differ from their North American counterparts are not well understood. A comparison between North and South American LLJs will be useful to disclose the physical processes that affect South American LLJs.

The previous questions need to be addressed via more adequate observations, such as those planned by the South American LLJ field experiment (Douglas 2000; Nogues-Paegle and Paegle 2000). However, prior to such observations, a clear characterization of the South American LLJs based on current available data would help determine what processes might be important and, consequently, help design an observational network for further studying and monitoring the South American LLJs. In the present study, we use a 15-yr reanalysis dataset to investigate the mechanisms responsible for South American LLJs. Results from this type of analysis are expected to provide some guidelines for monitoring South American LLJs, which, in turn, need to be validated through observations. Unlike traditional LLJ case studies, we take daily 850-hPa meridional winds as an index to represent the LLJ variation. In this way, the LLJs are a part of meridional wind variations in some extreme phase. Recent modeling studies (Byerle and Paegle 2002; Campetella and Vera 2002) have simulated the effects of mechanical blocking of upstream airflows by the Andes on the South American LLJ. Independently, we will show in this paper that the variation of the LLJs on synoptic time scales, as well as the meridional wind changes to the east of the Andes, are largely determined by upstream flow patterns of previous days. Therefore, the frequency and intensity of the South American LLJs vary with the seasonal change of upstream mean flow pattern and its response to the Andes. This mechanism enables us to explain the seasonal and intraseasonal variations of the South American LLJs and to potentially improve the forecast of strong LLJ events in winter, spring, and fall. In the next section, the dataset and methods are described. A comparison between North and South American LLJs is presented in section 3 to identify the differences in forcing the LLJs over the two continents. The role of upstream flow and lee cyclogenesis in the development of South American LLJs and the predictability of the LLJs are examined in sections 4 and 5, respectively. Section 6 discusses the relative importance of the upstream flow and local boundary layer processes in determining the South American LLJs and some processes responsible for the different behaviors between the North and South American LLJs. The influence of these LLJs on South American precipitation and their relation to tropical LLJs over the equatorial western Amazon (Wang and Fu 2002) and to the subtropical highs over the South Pacific and Atlantic Oceans are also explored. Conclusions are given in section 7.

2. Data and methods

For this study, we use the three-dimensional atmospheric wind field, geopotential height, sea level pressure (SLP), and precipitation from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA) on a 2.5° latitude $\times$ 2.5° longitude grid at 17 pressure levels. The data are 4 times daily at 0000, 0600, 1200, and 1800 UTC, respectively, and over a 15-yr period (1979–93). An evaluation by rain gauges, blended satellite and gauge observations, and radiosondes (Fu et al. 2001) suggests that, among the available reanalysis products, the ERA most closely captures the climatology of precipitation and related atmospheric fields over tropical South America. This dataset has also been used to study the seasonal variation of South American precipitation (Wang and Fu 2002) and the onset of the Amazon rainy season (Li and Fu 2003), indicating the usefulness of the ERA in the South American region. We expect that this dataset may help explore the mechanisms that control the seasonal variation of the South American LLJs and develop some hypotheses that can be evaluated when adequate observations become available in the future. The seasonal variation of the LLJs will be examined with monthly mean data. These seasonal changes are a manifestation of the changes in frequency and intensity of LLJ episodes that develop on a daily time scale. Therefore, in addition to monthly mean data, daily means are also used to resolve the day-to-day variation of the LLJs. The diurnal variation of the LLJs is not the focus of this study because its controlling process is expected to be different from those that govern the seasonal and synoptic variations of the LLJs. Due to lack of observations, the diurnal cycle of the South American LLJs is not yet understood. A comparison with mesoscale model forecasts also suggests that the ERA data probably underestimate the horizontal

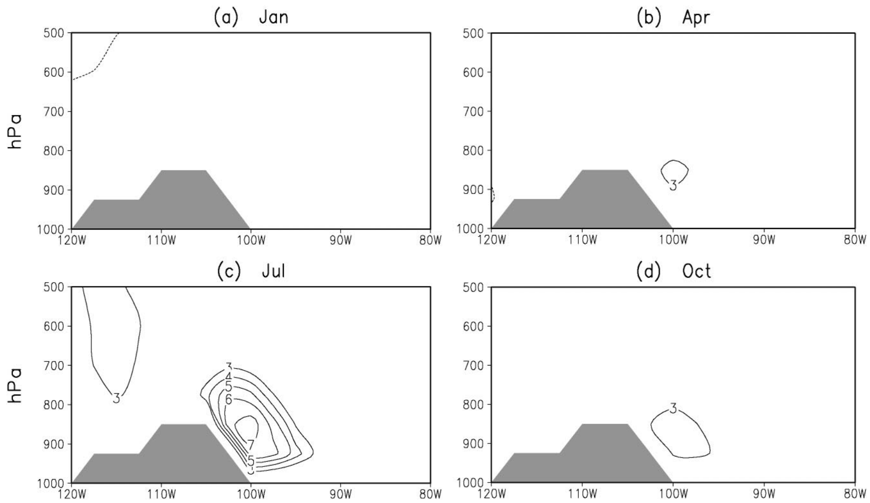

FIG. 1. Vertical–longitudinal cross section of monthly mean meridional winds at 35°N for (a) Jan, (b) Apr, (c) Jul, and (d) Oct. Contour interval is 1 m s^{-1} with negative values dashed. Contours between −3 and 3 m s^{-1} are omitted. Shadings are topography.

temperature gradients near the surface to the east of the Andes. This could consequently underestimate the contribution of boundary layer baroclinicity to the South American LLJ.

Two statistical methods, correlation and compositing, are used. The correlation analysis is capable of revealing a linear relationship between two variables. Composites based on either extreme events or linear regressions are used to obtain the spatial distributions of circulation and precipitation associated with the LLJs. It should be noted that LLJs may vary from case to case. While the composite analysis highlights common features among the strong LLJs, it is possible that some circulation patterns associated with particular LLJ episodes may not be selected by the composites.

3. Comparison between North and South American LLJs

Since both North and South American LLJs are oriented poleward, we can use monthly mean meridional winds to conveniently illustrate their seasonality. We chose the data from January, April, July, and October to represent each of the respective boreal and austral seasons. Figure 1 shows the vertical–longitudinal cross section of the monthly mean meridional winds at 35°N, where the Great Plains LLJs have the highest frequency of occurrence (Bonner 1968). The meridional winds have a strong seasonal variation. Large southerly winds occur only in northern summer with maximum winds over the eastern slopes of the Rockies between 900 and 850 hPa (Fig. 1c). This feature is consistent with both the location and season of the North American LLJs. Similar cross sections were made for South America at 15°S for January and 20°S for other months, as shown in Fig. 2. At these latitudes, the long-term mean meridional winds display low-level northerly wind maxima to the east of the Andes (not shown). A comparison between Figs. 1 and 2 indicates that the seasonal variation of the meridional winds in South America is weaker than that in North America. Moreover, the meridional winds to the east of the Andes are strongest in austral winter. The wind maximum (Fig. 2c) is similar to the summertime wind maximum in North America (Fig. 1c), but its location is away from the eastern slopes of the Andes, and the core of the LLJs is located at a higher altitude (850–800 hPa). Since radiosonde data in the South American LLJ region are scarce, the LLJs may strongly depend on the ERA model characteristics. It is worthwhile comparing monthly mean fields in different reanalysis data. The long-term mean meridional winds at the same latitudes from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) show an LLJ structure over South American with both horizontal and vertical locations similar to those in Fig. 2. The intensity of the wind maxima, however, is weaker in the NCEP–NCAR reanalysis than in the ERA, especially during austral fall. Overall, the aforementioned distinctions of seasonality and vertical extension between North and South American LLJs (Paegle 1998; Li and Treut 1999) are well reflected in the monthly mean meridional winds.

The variability of the LLJs is further examined using daily 850-hPa meridional winds averaged over areas where the LLJs frequently occur. We chose domains of (30°–40°N, 95°–105°W) and (15°–25°S, 55°–65°W) for North and South American LLJs, respectively. These area-averaged meridional winds are referred to hereinafter as the LLJ index. In austral summer months, the South American LLJs slightly shift toward the equator with a northwest–southeast orientation along the eastern

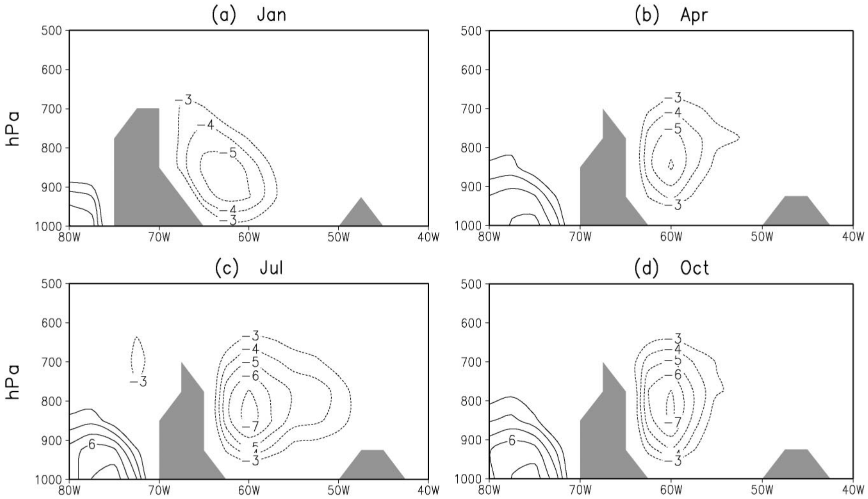

FIG. 2. As in Fig. 1 but at (a) 15°S and (b),(c),(d) 20°S over South America.

slopes of the Andes between 10° and 20°S. Thus, the January South American LLJ index is constructed in a parallelogram longitudinally bounded by (62.5°–72.5°W) at 10°S and (52.5°–62.5°W) at 20°S. In addition to summer LLJs over the two continents, the comparison also includes the South American LLJs in July since the South American LLJs are strongest in austral winter. Figure 3 shows the 15-yr daily North American LLJ index in boreal summer (July) and the South American LLJ index in austral summer (January) and winter (July), respectively. Over North America (Fig. 3a), the summer LLJ index is dominated by southerly winds. The frequency of occurrences for the poleward winds is 95%. The equatorward winds, if any, are much weaker. Over South America, the summer LLJ index (Fig. 3b) is also dominated by poleward winds, with a frequency of 93%. The poleward winds in the winter LLJ index (Fig. 3c) are much stronger than those in summer. The frequency of occurrences for northerly winds is 80%. There is still a 20% chance for strong equatorward winds to occur to the east of Andes in winter. Both the North and South American LLJ indices have a similar behavior in summer. The South American LLJ index in winter, however, is significantly different from the summer indices in terms of the frequency and intensity of the poleward winds.

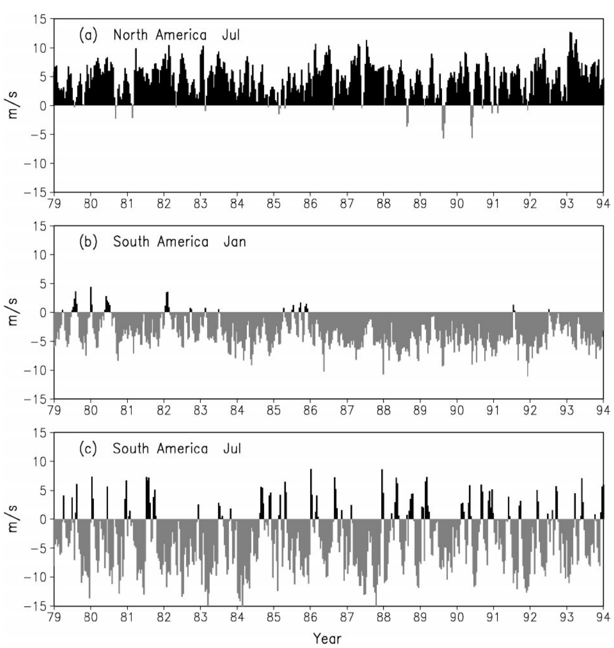

FIG. 3. Time series of 850-hPa daily mean meridional winds averaged over (a) North America (30°–40°N, 95°–105°W) in Jul, (b) South America bounded by (62.5°–72.5°W) at 10°S, and (52.5°–62.5°W) at 20°S in Jan, and (c) South America (15°–25°S, 55°–65°W) in Jul from 1979 to 1993. Dark (light) bars indicate southerly (northerly) winds.

The different dynamic processes responsible for the LLJs over North and South America can be inferred from circulation patterns associated with these LLJs. Figure 4 shows the composite maps of 925-hPa temperature and 850-hPa wind. The composites were made based on the top 20% of poleward wind events in the corresponding LLJ indices for North America (July with LLJ index > 7.05 m s^{-1}) and South America (January with LLJ index < -5.95 m s^{-1}; July with LLJ index < -9.26 m s^{-1}), respectively. These extremes have the major LLJ features with low-level maximum winds and an apparent nocturnal intensification, as shown in the composite vertical profiles of wind speed (Figs. 4b,d,f). Over the eastern slopes of the Rockies, there are large zonal temperature gradients at 925 hPa in summer months (Fig. 4a). Strong southerly winds at 850 hPa between 30° and 40°N are nearly parallel to the isotherms in the lower atmosphere. Strong diurnal changes in surface heating during northern summer may lead to a diurnal variation of zonal temperature gradients over the slopes, and further enhancement of nocturnal southerly winds above through the thermal wind (Bonner and

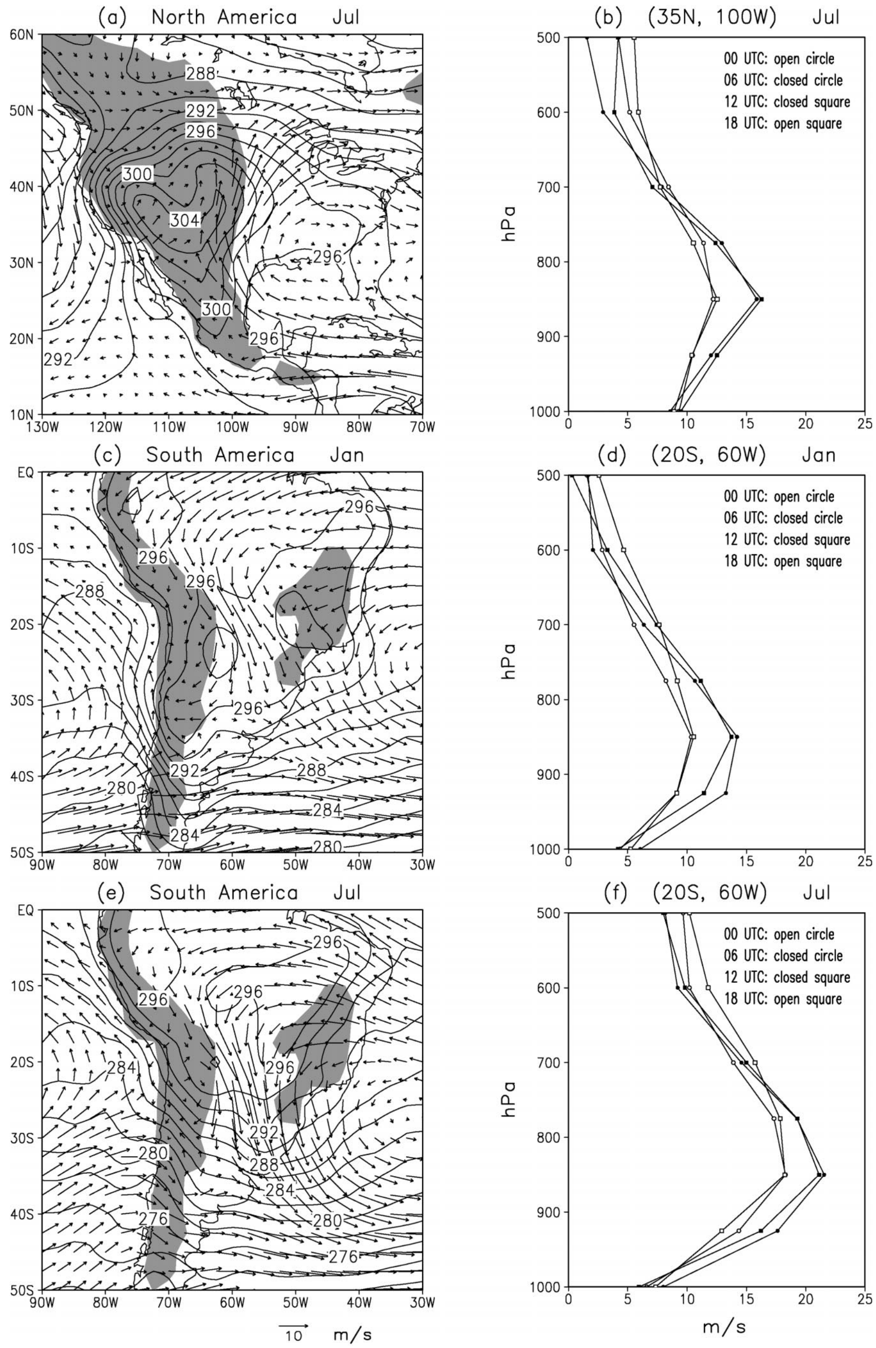

FIG. 4. Composites of 925-hPa temperature (contours) and 850-hPa wind (vectors) for (a) North America in Jul, South America in (c) Jan, and (e) in Jul, and vertical profiles of horizontal wind for 0000, 0600, 1200, and 1800 UTC at (b) 35°N, 100°W, and (d), (f) 20°S, 60°W, based on top 20% of poleward wind events in corresponding LLJ index. Contour interval is 2 K. Shadings indicate topography.

Paegle 1970). Over South America, in contrast, there is no strong zonal temperature gradient in the lower atmosphere in the presence of the LLJs in austral summer (Fig. 4c). The LLJs are largely normal to the isotherms in austral winter (Fig. 4e). The different configurations in thermodynamic structure between the circulations associated with North and South American LLJs suggest that the mechanism responsible for the North American LLJs, especially the baroclinicity in the lower atmosphere, may not be the main cause of the South American LLJs.

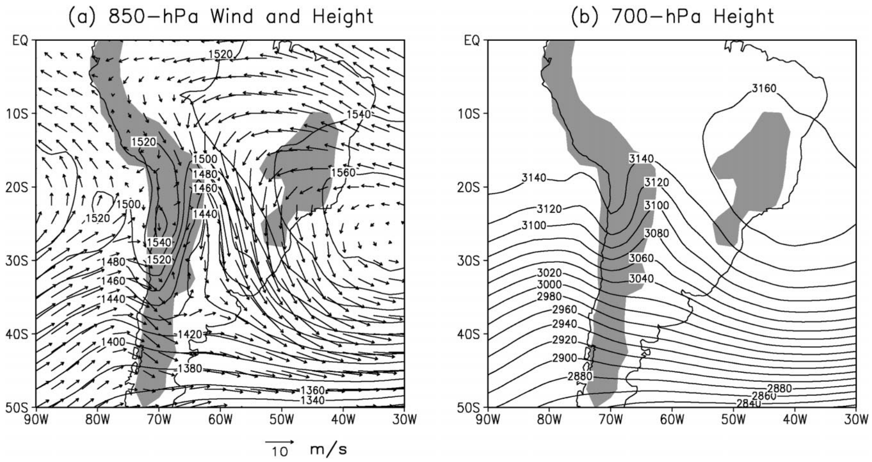

FIG. 5. Composites of Jul (a) 850-hPa wind (vectors) and height (contours) and (b) 700-hPa height, based on top 20% of northerly events in South American LLJ index. Contour interval is 20 m. Shadings indicate topography.

4. Roles of upstream large-scale circulation

The large-scale circulation's control of the South American LLJs is investigated using composites of wind and geopotential height at 850 hPa (Fig. 5a) and geopotential height at 700 hPa (Fig. 5b), based on the top 20% of northerly wind events selected for Fig. 4c. The analysis focuses on July since the jets are strongest in austral winter and also very distinct from the North American LLJs. At 850 hPa, a ridge is found over the Andes and a trough to the east of the Andes (Fig. 5a). The subtropical LLJs around 55°W are nearly parallel to the height contours. In the jet region (15°–35°S, 50°–60°W), geostrophic winds account for 80% of meridional winds. The strong northerly flow is thus maintained by the zonal height gradients associated with the lee trough through the geostrophic balance. The latter is closely related to orographically induced pressure disturbances and lee cyclogenesis (Smith 1982). The disturbances induced by the Andes decrease with altitude and mainly exist below 500 hPa. The typical flow pattern as the air crosses a mountain is clearly seen in the 700-hPa height field, with a ridge on the windward side and a trough on the leeward. The results presented in Fig. 5 reveal that the effect of the Andes on the airflow probably leads to the large zonal pressure gradients needed for the development of the northerly LLJs.

The aforementioned mechanism is also supported by the evidence that the South American LLJ index highly correlates with the upstream zonal winds of preceding days, as shown in Fig. 6. Significant negative correlations are found over the subtropical South Pacific when 700-hPa zonal winds lead the LLJ index (Figs. 6a,b). The negative correlations indicate that the larger the westerly winds upstream, the stronger the northerly LLJs to the east of the Andes. The center of maximum correlations approaches the Andes, increases with time prior to day 0, and decays rapidly after day 0. The results indicate a strong association between the northerly LLJs and the westerly flow across the Andes. Similar correlation patterns are also found in April and October, but not in January (not shown). It suggests that the LLJs in austral spring and fall are also likely induced by the flow interaction with the Andes. In summer other factors, such as the gradients of surface fluxes and temperature and Amazon convection, may become increasingly important for the LLJs (Kleeman 1989; Figueroa et al. 1995).

To explore a possible link between the LLJs and upper-level circulation, Fig. 7 shows lead and lag correlations of 250-hPa height with the LLJ index. A center of positive correlations appears in the South Pacific around 40°S and moves eastward when the upper-level circulation leads the LLJ (Figs. 7a–c). Its location becomes stationary over the Andes when the circulation lags the LLJ (Figs. 7d,e). The positive correlations increase with time before day 0 and decrease after that. Starting from day −2, two centers of alternating negative and positive correlations develop downstream over southern Brazil and the South Atlantic. Figure 7, together with lead and lag regression patterns of the 250-hPa height against the LLJ index (not shown), suggests that a strong northerly LLJ is generally associated with an upper-level trough propagating eastward. When the trough approaches the Andes, it is intensified and followed by a successive amplification of a ridge and a trough farther downstream.

The relationship between the northerly LLJs and the upper-level trough also has a manifestation in the lower atmosphere. Figure 8 shows the correlations of 700-hPa height with the LLJ index for the height leading the LLJs by up to 4 days. The positive correlations to the west of the Andes are greater at 700 hPa than those at 250 hPa (Figs. 8a,c,e versus Figs. 7a,b,c, respectively). The center of maximum correlations at 700 hPa is lo-

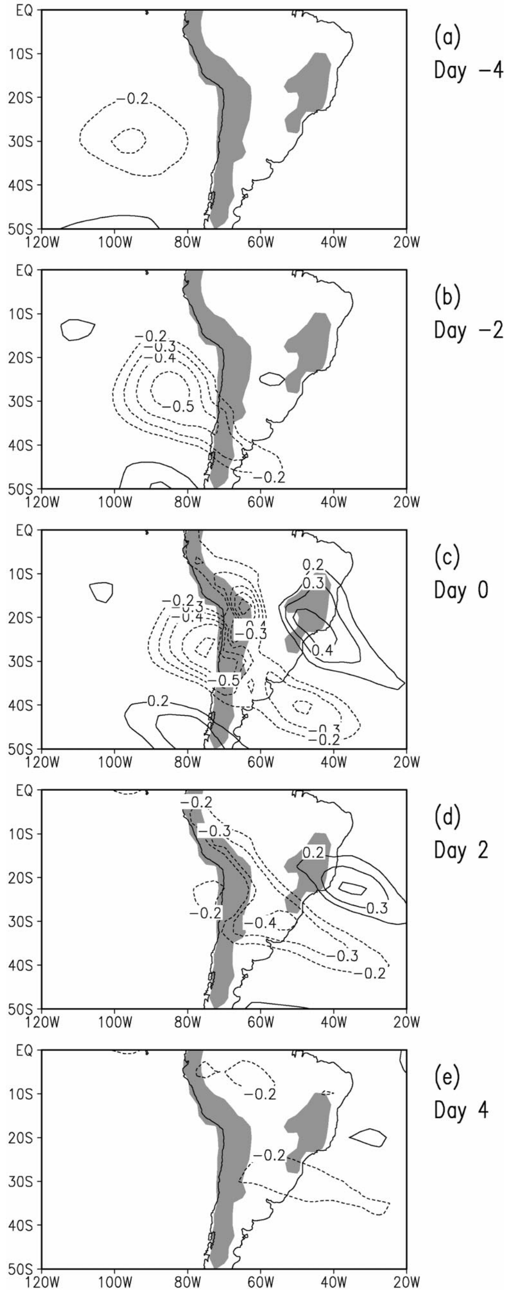

FIG. 6. Lead and lag correlations between 700-hPa zonal wind and South American LLJ index, using 15-yr daily data for Jul. Correlation maps are shown for zonal wind leading the LLJ index by (a) 4, (b) 2, and (c) 0 days, and lagging by (d) 2 and (e) 4 days. Contour interval is 0.1 with negative values dashed. Contours between −0.2 and 0.2 are omitted. Shadings are topography.

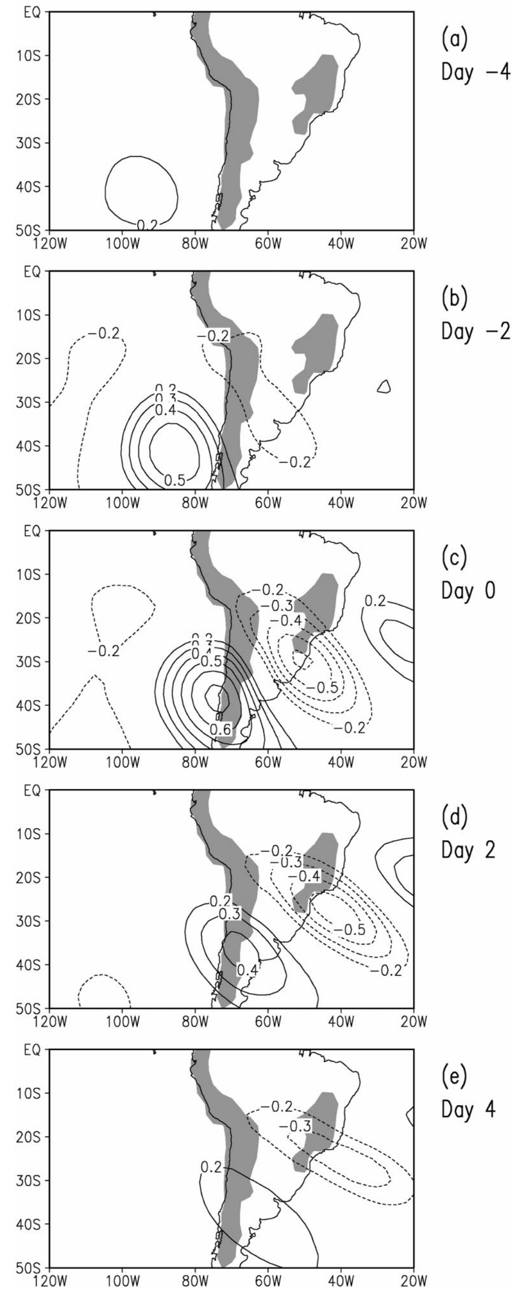

FIG. 7. Correlations of 250-hPa height with the LLJ index in Jul for the height leading the LLJ index by (a) 4, (b) 2, and (c) 0 days, and lagging by (d) 2 and (e) 4 days. Contours and shadings are the same as in Fig. 6.

cated to the east of the corresponding center at 250 hPa, indicating that the trough axis tilts westward with height. The evolution of the upper-level circulation in Fig. 7 thus involves the development of a baroclinic system and dispersion of its energy downstream (Holton 1992). The development of baroclinic waves over the Andes, in addition to the effect of mechanical blocking, is also likely responsible for the lee cyclogenesis critical to the LLJs.

A close inspection of Figs. 6 and 8 reveals that significant negative correlations of 700-hPa zonal wind with the LLJ index (Figs. 6a–c) occur in the northern flank of the positive correlation centers in the height field (Figs. 8a,c,d). Therefore, the strong zonal winds in the South Pacific prior to the occurrence of the north-

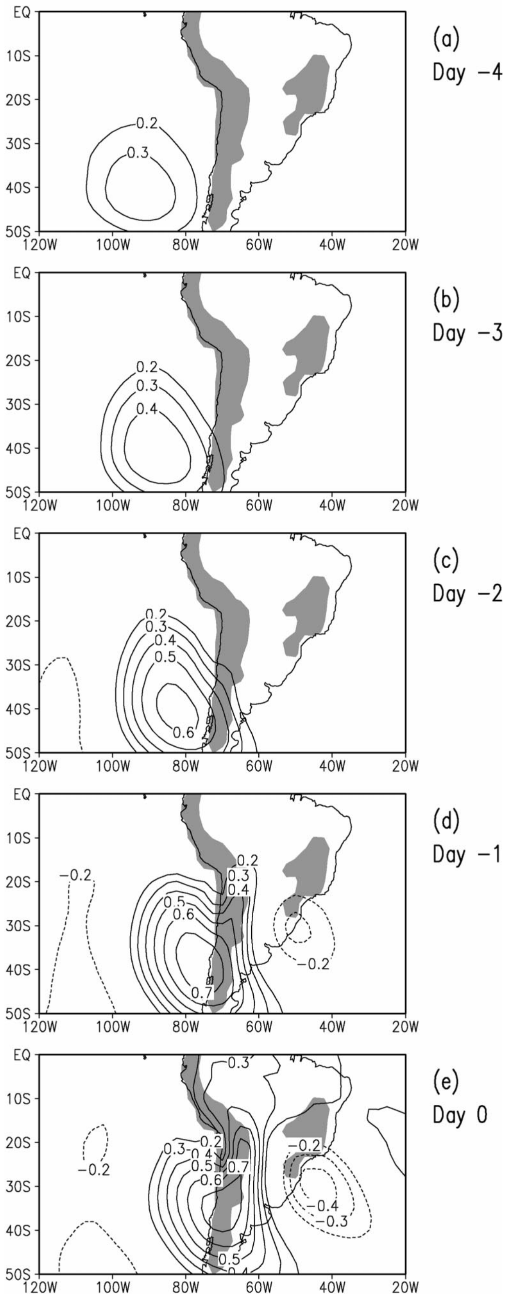

FIG. 8. Correlations of 700-hPa height with the LLJ index in Jul for the height leading the LLJ index by (a) 4, (b) 3, (c) 2, (d) 1, and (e) 0 days. Contours and shadings are the same as in Fig. 6.

erly LLJs are actually a part of the lower-level cyclonic circulation associated with the upper-level trough. In addition to the pressure decrease caused by the baroclinic development of the upper-level trough, strong zonal winds associated with the trough can be deflected and also lower the atmospheric pressure on the lee side when crossing the Andes (Smith 1982). This process is probably responsible for the tongue of relatively strong correlations extending from 30° to 20°S along the Andes at day −1 and day 0 (Figs. 8d,e). It is evident that both mechanisms contribute to the lee cyclogenesis critical to the development of the northerly LLJs.

As indicated by the South American LLJ index (Fig. 3c), strong southerly winds can occur occasionally in the LLJ region during winter. These southerly winds also have an LLJ structure with low-level wind maximums (not shown), though these maximum winds are weaker than the northerly LLJs. It is expected from Figs. 6–8 that the southerly LLJs tend to occur when a ridge replaces the upstream trough and the zonal cross-Andes flow is weak. To illustrate how the LLJs reverse from northerly to southerly, we analyzed composites of 850-hPa horizontal winds and 700-hPa heights based on lead and lag linear regressions against the 15-yr July daily LLJ index (Fig. 9). These composites correspond to an LLJ index of 5 m s^{-1} southerly at day 0. Both the lee trough and the northerly LLJ exist 4 days before (day −4) the strong southerly LLJ (Fig. 9a). At day −4, there are also an anticyclonic circulation in the 850-hPa wind field and a weak ridge centered at 95°W in the 700-hPa height field. As the subtropical disturbance moves eastward at day −3 (not shown) and day −2 (Fig. 9b), the anticyclonic circulation becomes stronger and a deep ridge appears in the South Pacific. The northerly flow to the east of the Andes decays gradually and disappears at day −2. At day −1 (not shown) the lee trough is completely distorted by the subtropical high near the west coast. A strong southerly emerges to the east of the Andes between 25° and 35°S. When the anticyclonic system crosses the Andes, the southerly winds penetrate further equatorward (Fig. 9c). A southerly LLJ is thus well developed at day 0. At day 1, the southerly LLJ disappears quickly (not shown). As the upstream circulation returns to its prevailing zonal-flow pattern during day 2 and day 4 (Figs. 9d,e), the northerly LLJs are reestablished on the lee side of the mountain. The evolution of the southerly LLJ in Fig. 9 clearly shows a link between the eastward movement of the anticyclonic circulation disturbance over the South Pacific and the reversal of the LLJs from northerly to southerly. It should be noted that the levels of 850 and 700 hPa are below the higher portions of the Andes. This may compromise the details of the small-scale anticyclonic ridge appearing just over the Andes (Figs. 5 and 9). A similar composite of surface temperature (not shown) suggests a significant drop in temperature over central South America in the presence of a southerly LLJ. In fact, the southerly LLJ events are often associated with the intrusion of cold air masses northward during austral winter (e.g., Fortune and Kousky 1983; Marengo et al. 1997; Garreaud 2000). The strengthening of the anticyclonic circulation across the Andes when a southerly LLJ occurs has also been clearly described in Fortune and Kousky (1983).

The dependence of the South American LLJs on the upstream circulation and lee cyclogenesis can also be seen in the changes of upstream 700-hPa zonal wind

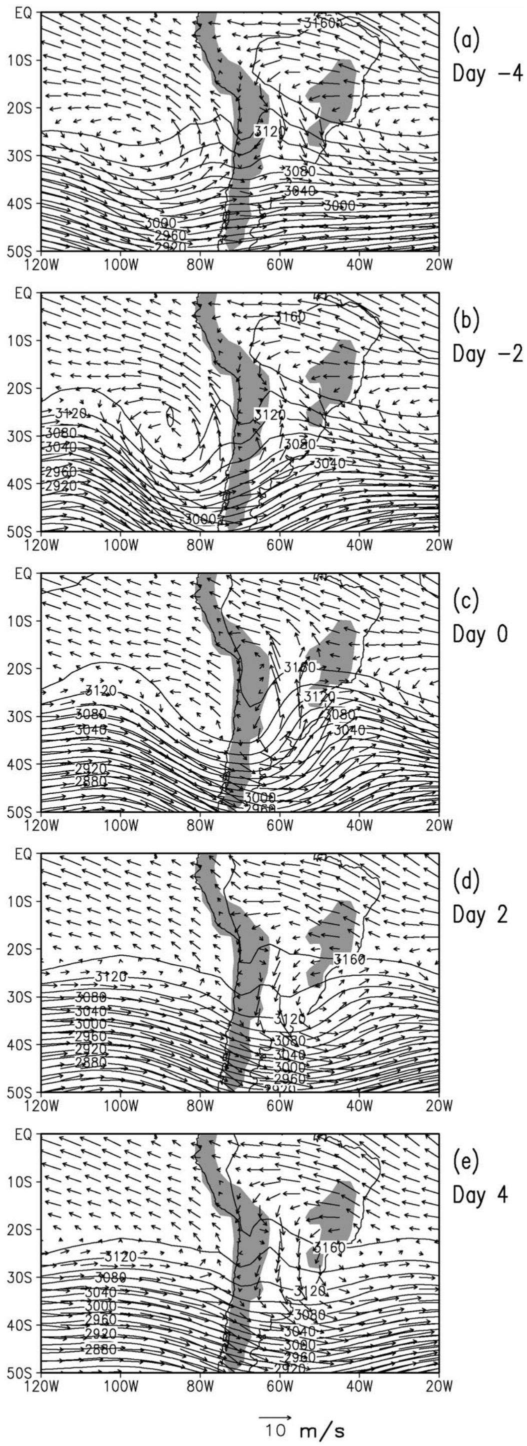

FIG. 9. Regression patterns of Jul 850-hPa wind (vectors) and 700-hPa height (contours) associated with a 5 m s^{-1} southerly wind in the South American LLJ index. Composite maps are shown for circulation leading the LLJ index by (a) 4, (b) 2, and (c) 0 days, and lagging by (d) 2 and (e) 4 days. Contour interval is 20 m.

and leeside 850-hPa height with the LLJ index (Fig. 10), based on linear regressions upon the 15-yr daily LLJ index in July. The zonal wind is examined at 25°S, since the maximum contemporary correlation between the zonal wind and the LLJ index is found at this latitude (Fig. 6c). In general, a strong northerly (southerly) LLJ is associated with large westerly (small westerly or even easterly) winds between 70° and 95°W (Fig. 10a), and also associated with a trough (ridge) on the lee side of the Andes (Fig. 10b). As the lee trough is intensified with the zonal wind, the slope of the height between 50° and 60°W becomes steeper. This increases the zonal gradient of the geopotential height and further enhances the northerly LLJs through the geostrophic balance.

The mechanisms of the LLJs due to the upper-level trough and associated westerly flow crossing the Andes provide a physical explanation for the seasonal variation of the South American LLJs. In austral summer, the upstream low-level circulation is dominated by the subtropical high over the South Pacific. Consequently, zonal westerly winds are generally weak. Hence, the lee trough-induced meridional winds are weaker in January. This process accounts for the observed overall weaker South American LLJs in summer. There are, however, some episodes of strong northerly LLJs that can occur in summer, as reported in Douglas et al. (1998) and Marengo et al. (2002). In the winter season, the subtropical high shifts towards the equator. The extratropical circulation over the South Pacific is characterized by strong zonal flow (e.g., Newton 1972). The wind pattern favors the northerly LLJs downstream, consistent with strong northerly LLJs and relatively large meridional winds in July (Fig. 2c).

5. Predictability of South American LLJs based on the upstream zonal wind

Significant correlations between the LLJ index and upstream zonal winds of previous days (Figs. 6a,b) suggest that the zonal winds over the subtropical South Pacific may be used as a predictor for South American LLJs. Given a 700-hPa zonal wind pattern, the LLJ index can be predicted based on the relationship depicted by linear regressions. The usefulness of this forecast method and the predictability of the South American LLJs are evaluated by a cross-validation technique using the 15-yr July daily data. First, we constructed a set of 15-yr daily zonal wind indices by averaging 700-hPa zonal winds over the regions exhibiting strong correlations with the LLJ index. Since the regions of strong correlations change with the number of days that zonal winds lead the LLJs (Fig. 6), the regions for averaging zonal winds vary from day −5 to day −1, as listed in Table 1. We took both the zonal wind index and the LLJ index of one target month out from the data and performed a linear regression analysis on the rest of the 14-yr July daily data. Hindcasts of daily LLJ index were then made for the target

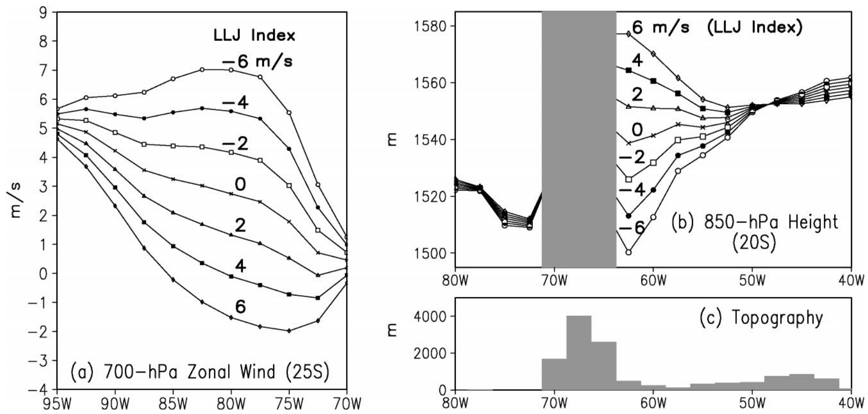

FIG. 10. Composites of (a) 700-hPa zonal wind at 25°S and (b) 850-hPa height at 20°S for different values of the LLJ index, based on the linear regression against the 15-yr daily LLJ index in Jul. (c) Topography along 20°S.

month using the zonal wind index of that month and the relationship between the zonal wind index and the LLJ index depicted by the linear regression. The same procedure was repeated for July of each year and for different lead times of zonal winds with respect to LLJs. Both the observed (ERA assimilated) and predicted LLJ indices were then evenly divided into five categories, respectively. Each of the five categories represents 20% of the total LLJ index samples classified according to the magnitude of the LLJ indices. For the observed LLJ index, the five categories are: I, with the LLJ index between −9.25 and −16.90 m s^{-1} (upper 20%); II, with the index between −6.65 and −9.25 m s^{-1} (60%–80%); III, with the index between −3.60 and −6.65 m s^{-1} (40%–60%); IV, with the index between 0.10 and −3.60 m s^{-1} (20%–40%); and V, with the index between 0.10 and 8.65 m s^{-1} (lower 20%). Thus, class I represents the strongest northerly LLJs and class V the southerly winds. A hit rate was used to measure the predictive skill, which is the ratio of number of hits when both the observed LLJ index and hindcasts fall into the same category versus the total number of events (31 × 15 = 465). Figure 11 shows the hit rates for hindcasts made at different days from day −5 to day −1. Since each category consists of 20% of the total daily events, the percentage of hit by a pure guess is 20%. If the hindcasts are made simply by assuming that the LLJs persist in the following days, the hit rates for 3-day or longer predictions are similar to those of pure guess. The hit rates are increased for 2-day (24%) and 1-day (36%) forecasts. This indicates that though the northerly winds frequently occur to the east of the Andes, their intensities are highly variable. The hit rate based on persistence sets a bottom line for prediction. Any forecast with a hit rate lower than that of persistence has no predictive skill. Overall, the hit rates of hindcasts based on upstream zonal wind are higher than those based on the persistence, indicating a certain degree of predictability of South American LLJs. The forecast skills are much better for extreme cases (classes I and V). For the extreme northerly category (I), the hit rate increases to 35% for 3-day forecasts and to 53% for 1-day forecasts. For the extreme southerly category (V), the hit rate increases to 41% for 3-day forecasts and to 55% for 1-day forecasts. This cross validation thus suggests that the upstream zonal wind is an important parameter for predicting the South American LLJs. From the forecasters' point of view, it would be more

TABLE 1. Domains for averaging 700-hPa zonal winds used as a predictor for South American LLJ forecasts.

Day	Domain	
Day −5	27.5°–32.5°S	102.5°–107.5°W
Day −4	27.5°–32.5°S	92.5°–97.5°W
Day −3	27.5°–32.5°S	87.5°–92.5°W
Day −2	25°–30°S	82.5°–87.5°W
Day −1	25°–30°S	77.5°–82.5°W

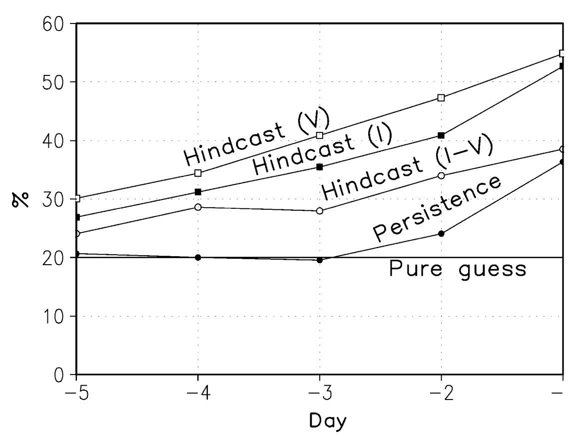

FIG. 11. Percentages of hit between the LLJ index and those of hindcasts based on pure guess (no marks), persistence (closed circles), and upstream zonal winds for all five-category LLJs (open circles), and for categories I (closed squares) and V (open squares), respectively. These hindcasts are made in different days from day −5 to day −1.

relevant to compare the forecast skill in Fig. 11 to the predictive capability of current numerical weather prediction models. This task together with the implementation of upstream zonal wind to improve daily LLJ forecasts will be our future work.

6. Discussion

a. Relative importance of upstream zonal flow and local boundary layer process

We have demonstrated that the northerly LLJs to the east of the Andes are maintained by strong zonal pressure gradients caused by the upper-level trough and westerly flow crossing the Andes through lee cyclogenesis. Two mechanisms are involved in this process. One is baroclinic development of the upper-level trough and the other mechanical blocking of the westerly flow by the Andes. Unlike North American LLJs, Fig. 4 has shown that the boundary layer baroclinicity does not contribute to the South American LLJs, at least in winter, spring, and fall. However, forecasts with a higher-resolution mesoscale model do indicate stronger zonal temperature gradients along the eastern slope of the Andes when the LLJs occur, especially in austral summer (P. L. Silva Dias 2003, personal communication). In comparison, the temperature gradients associated with the LLJs in ERA (Fig. 4c) are weaker than those in the mesoscale model forecasts. Thus, the effect of boundary layer baroclinicity on the South American LLJs is underestimated by ERA. To what degree such an effect may be more important than that indicated by ERA should be addressed in future using the in situ observations from the South American LLJ field experiments. In addition, the diurnal variation of vertical momentum mixing and the inertial oscillation of the wind (Blackadar 1957) in the PBL are still expected to be important. Our results suggest that the lee cyclogenesis responding to the upper-level trough and associated lower-level westerly wind is likely the main source of momentum for the LLJs. The boundary layer processes may regulate the vertical structure and diurnal cycle of the LLJs, and also modify the strength of the LLJs through their control on the turbulent frictional drag. The relative importance between the upstream circulation and the boundary layer processes may also vary seasonally. For example, during austral winter when the surface heating and the turbulent mixing within the PBL are weak, the strength of the LLJs may be more dominated by the upstream circulation. The diurnal changes of the LLJs may be smaller relative to their daily mean. During summer when surface heating and turbulence mixing are strong, the boundary layer processes likely become more important to the intensity, diurnal cycle, and vertical structure of the South American LLJs. Hence, determining the role of the PBL is still a key to an overall understanding of the South American LLJs. Validation of the aforementioned speculations via future observations would greatly help determine the relative importance of large-scale circulation and local PBL processes to the South American LLJs.

b. Processes responsible for the differences between North and South American LLJs

The lee trough mechanism proposed in this study enables us to explain some of the apparent differences between the South and North American LLJs. For example, the stronger South American LLJs in winter are consistent with stronger cross-Andes zonal flow as a result of the equatorward shift of the subtropical jet and stronger lee troughs. Because the momentum source of the South American LLJs is primary in the free atmosphere, the core of the LLJs is expected to be higher than for those dominated by the boundary layer processes. Occasional reversals of the South American LLJs on synoptic time scales can be explained by the occurrence of anticyclonic flow passing over the Andes. The life cycle of the lee troughs may compete with the diurnal cycle of the PBL processes in determining the diurnal variation of the South American LLJs. For example, a strongly deepened lee trough in late afternoon may offset the influence of the turbulent drag in the PBL and lead to a late-afternoon wind maximum, instead of an early-morning peak of the LLJs. The latter has been reported by Berri and Inzunza (1993) and Douglas et al. (1998).

c. Relations to precipitation, tropical LLJs, and subtropical highs

South American LLJs act as a moisture pipeline linking the Amazon to central South America (Paegle 1998). Consequently, the day-to-day fluctuations in the LLJs may significantly influence precipitation over both tropical and extratropical South America. Figure 12 shows the linear regression coefficients of precipitation against the LLJ index, based on the 15-yr daily mean precipitation from the ERA data for January, April, July, and October, respectively. These coefficients are actually the rates of change in precipitation associated with a 1 m s^{-1} increase of southerly wind in the LLJ index. Overall, the spatial patterns of the regression coefficients are similar in different seasons, with positive coefficients in tropical and subtropical South America and negative coefficients centered at 30°S. The northerly LLJs (negative index) move moisture from the Amazon basin to central South America. This leads to an enhancement of low-level moisture convergence over the La Plata river basin but moisture divergence over the Amazon, as implied by negative and positive rainfall coefficients in the two regions. The associations between precipitation and the LLJs are strongest in austral summer (Fig. 12a) and weakest in winter (Fig. 12c). Associated with a 5 m s^{-1} northerly LLJ, precipitation can be decreased

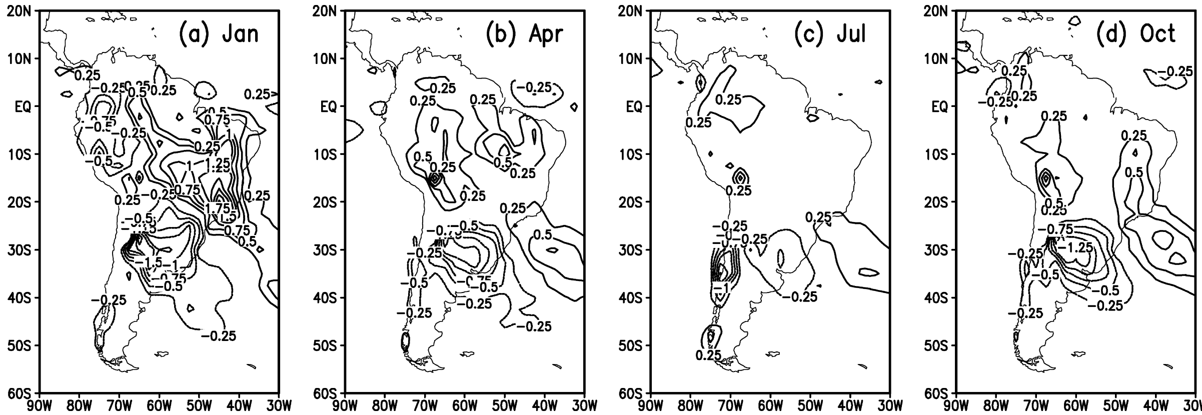

FIG. 12. Linear regression coefficient for (a) Jan, (b) Apr, (c) Jul, and (d) Oct daily precipitation from ERA data associated with the 15-yr daily mean LLJ index. Contour interval is 0.25 (mm day^{-1}) $(m\ s^{-1})^{-1}$. Zero contours are omitted.

(increased) by 7.5 mm day^{-1} over the eastern Amazon (La Plata river basin) in January. Figure 12 indicates that the precipitation and associated convection in the La Plata river basin (Velasco and Fritsch 1987) can be significantly enhanced by the northerly LLJs. It is interesting to note that precipitation over the South Atlantic convergence zone (SACZ) and that over northern Argentina and southern Brazil in Fig. 12 are out of phase in all seasons. A northerly (southerly) LLJ is thus associated with weakening (intensification) of the SACZ. A similar relationship has been documented by Nogues-Paegle and Mo (1997) for austral summer.

Wang and Fu (2002) found that South American precipitation is highly correlated with low-level cross-equatorial winds over the western Amazon. They constructed a wind index, the so-called V index, to represent the variability of the cross-equatorial winds, based on area-averaged (5°S–5°N, 65°–75°W) daily 925-hPa meridional winds. When the V index is southerly, precipitation is mainly confined to north of the equator. When the V index is northerly, precipitation is shifted toward the Amazon. The cross-equatorial winds also have an LLJ-like structure (Wang and Fu 2002, their Fig. 2b). To explore any relationship between the tropical and subtropical South American LLJs, Fig. 13 shows the lead and lag correlations between the LLJ index and the V index. In April, July, and October (Figs. 13b–d), the two indices are positively correlated when the LLJ index leads the V index by 1–2 days. This relationship suggests a possible influence of the subtropical LLJs on the cross-equatorial winds. The relationship is strongest in July, the Amazon dry season. In January, the wet season, both the lead and lag correlations are negative and significantly different from those in other seasons. Since both the associations of Amazon rainfall with the LLJ index and the V index are strongest in January (Fig. 12a; Wang and Fu 2002, their Fig. 10b), some feedbacks related to Amazon rainfall are likely involved in the relationship between the tropical and subtropical LLJs in the wet season (Kleeman 1989; Figueroa et al. 1995). The negative correlations in Fig. 13a suggest that southerly LLJs in the subtropics are associated with the northerly V index in the Tropics, both of which favor summer precipitation over the Amazon basin.

The feedback between the subtropical LLJs and Amazon rainfall in the wet season may also be inferred from the correlations of SLP with the LLJ index, as shown in Fig. 14. Over the Amazon and central Brazil,

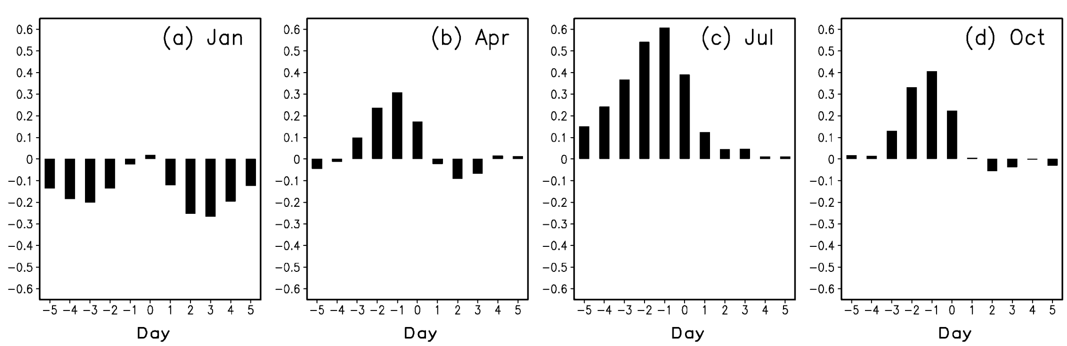

FIG. 13. Lead and lag correlations between the LLJ index and the V index, as defined by Wang and Fu (2002), for (a) Jan, (b) Apr, (c) Jul, and (d) Oct, using 15-yr daily data. Day −1 (1) denotes that the LLJ index leads (lags) the V index by one day.

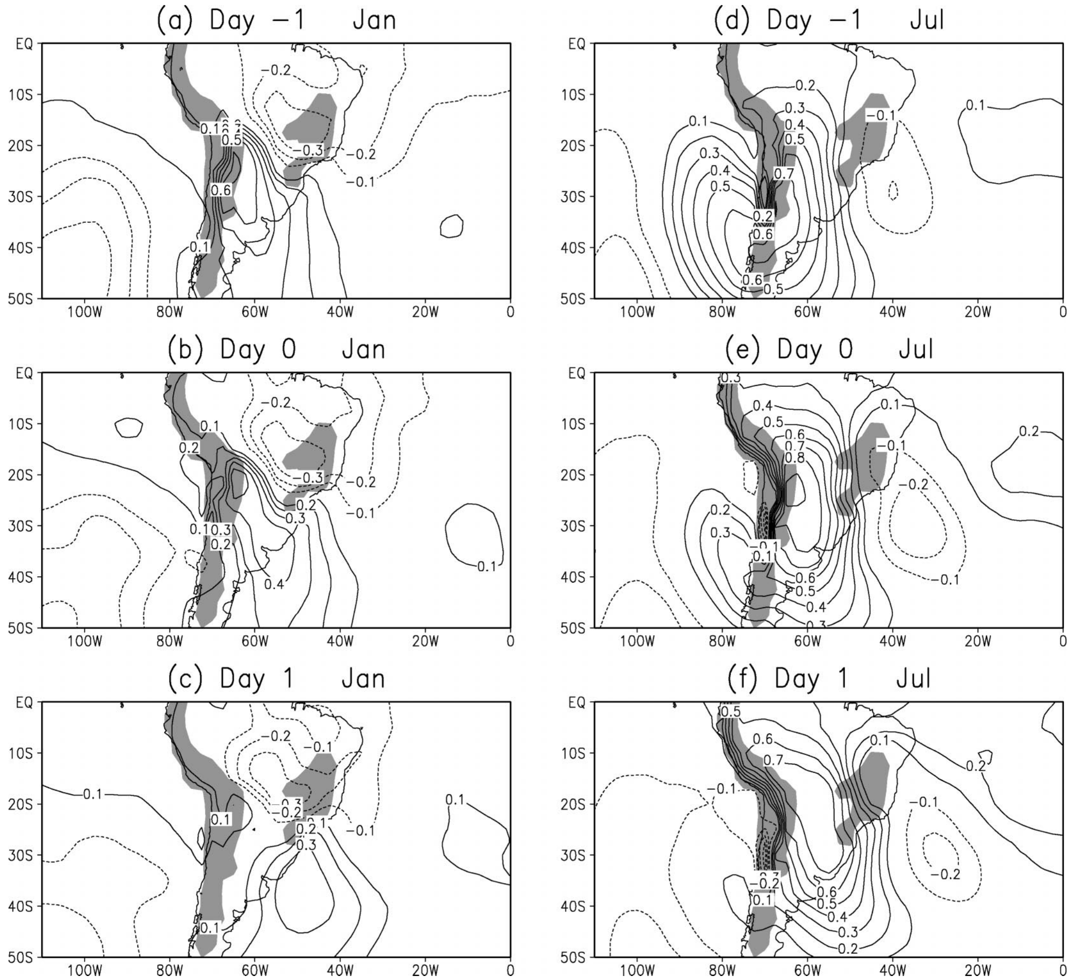

FIG. 14. Lead and lag correlations between SLP and the LLJ index for (a), (b), (c) Jan and (d), (e), (f) Jul, using 15-yr daily data. Correlation maps are shown for SLP leading the LLJ index by (a), (d) 1 day, (b), (e) 0 day, and (c), (f) lagging by 1 day. Contour interval is 0.1 with negative values dashed. Zero contours are omitted. Shadings are topography.

both the lead and lag correlations between SLP and the LLJ index are strong in January (Figs. 14a–c). The southerly LLJs can enhance low-level convergence and thus precipitation over the Amazon basin. The diabatic heating associated with rainfall over the Amazon and central Brazil, in turn, can modulate the LLJs through the lower-level circulation over northern Argentina in response to the tropical heating (Silva Dias et al. 1983; Kleeman 1989; Figueroa et al. 1995). The large positive and negative correlations over central South America and the South Pacific, when the SLP leads the LLJs by 1 and 0 day (Figs. 14a,b), suggest that southerly (northerly) LLJs are influenced by high (low) SLP east of the Andes and weakening (deepening) of the subtropical high over the South Pacific. In July (Figs. 14d–f), the correlation maps clearly illustrate that the occurrence of the LLJs is related to the eastward movement of pressure systems from the South Pacific across the Andes. The results support the earlier mechanism, that the variation of the LLJs is controlled by the changes in the upstream circulation pattern. The LLJs are thus sensitive to the location of the subtropical high in the South Pacific. The positive correlations to the east of the Andes extend farther toward the Tropics at day 1 (Fig. 14f), indicating an influence on the tropical circulation from the extratropics. It is consistent with the lead and lag correlations between the LLJ index and the V index (Fig. 13c). In July, the dry season, heavy precipitation is confined to north of the equator. Whether the tropical heating affects the subtropical LLJs was examined via lead and lag correlations of the LLJ index with precipitation (not shown). No significant correlations are found over equatorial South America when precipitation leads the LLJs. The result suggests that the subtropical LLJs are less affected by the tropical convection in winter.

The relationships between the LLJs and subtropical highs are depicted by the composites of SLP, based on the linear regressions against the 15-yr daily LLJ index. Figure 15 shows the SLP patterns associated with the LLJ index of 5 and -5 m s^{-1} for January and July,

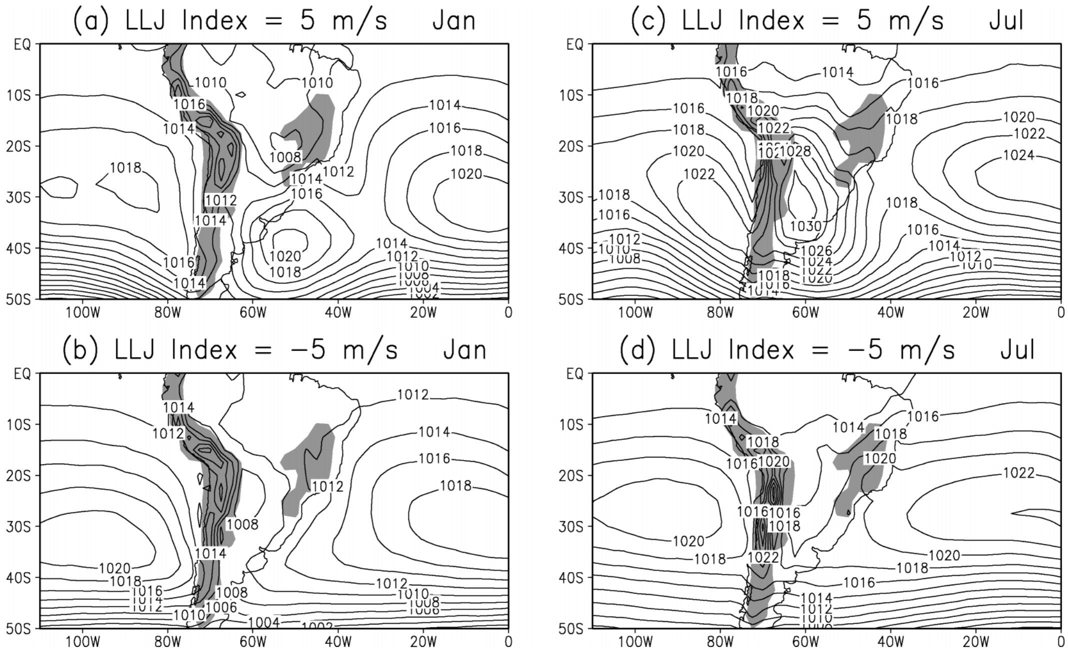

FIG. 15. (a), (b) Jan and (c), (d) Jul SLP fields associated with different LLJ indices, obtained using the linear regression against the 15-yr daily LLJ index. Regression patterns are shown for the LLJ index equal to (a), (c) 5 m s^{-1} and (b), (d) −5 m s^{-1}. Contour interval is 2 hPa. Shadings are topography.

respectively. In January, the subtropical high over the South Pacific displays a poleward (equatorward) shift in the presence of a northerly (southerly) LLJ in Fig. 15b (Fig. 15a). The center of the subtropical high over the South Atlantic does not change significantly between the northerly and southerly LLJs. However, a strong surface high appears to the east of extratropical South America when the southerly LLJs occur. Associated with the southerly (northerly) LLJs, the subtropical high over the South Pacific tends to be weaker (stronger) and the subtropical high over the South Atlantic stronger (weaker). The relationship is consistent with the negative and positive correlations over the two southern oceans (Fig. 14b), respectively. From the SLP patterns, it is also easy to identify a strong (weak) SACZ in the southerly (northerly) LLJ case, as discussed in Nogues-Paegle and Mo (1997). In July, when there is a southerly LLJ (Fig. 15c), a strong anticyclone is just off the west coast and high pressures dominate over central South America. The extratropical circulation exhibits a wavy pattern. In the northerly event (Fig. 15d), the subtropical high over the South Pacific returns to its climatological mean position. Zonal flow prevails throughout the extratropics, a favorable situation for the northerly LLJs. The LLJs are relatively insensitive to the variation of the subtropical high over the South Atlantic Ocean, since it is located farther downstream when the zonal flow crosses the Andes. Clearly, the relationship between the LLJs and the subtropical highs is seasonally dependent.

7. Conclusions

Based on area-averaged daily mean 850-hPa meridional winds from 1979 to 1993 provided by the ERA, we constructed an LLJ index for comparing the seasonal variability, spatial structure, and forcing of both North and South American LLJs. The ERA is able to reproduce the key differences between the North and South American LLJs based on limited available observations reported in previous studies. For example, the North American LLJs along the eastern slopes of the Rockies occur mainly in summer months. In contrast, the South American LLJs to the east of the Andes exist throughout the year and are strongest in austral winter. The poleward winds in the North American LLJ region are very persistent in July. In the South American LLJ region, the meridional winds can be either poleward or equatorward, though the latter are less frequent. The North American LLJs are largely caused by the diurnal variation of zonal temperature gradients in the lower atmosphere due to surface heating and changes of surface elevation over the terrain. However, our analysis indicates that there are no apparent zonal temperature gradients to the east of the Andes responsible for the South American LLJs.

The relationship between the LLJ index and large-scale circulation suggests that the South American LLJs in austral winter are caused by the interaction of the upper-level trough and associated low-level zonal winds with the Andes. The northerly LLJs are maintained by strong zonal pressure gradients due to the lee cyclogenesis. This process involves both the baroclinic development of the upper-level trough and the deflection of the westerly flow crossing the Andes. The effect of boundary layer baroclinicity on the LLJs appears to be not as important as that of the lee trough, especially during winter. Whether it becomes more important in summer remains unclear because ERA probably underestimates the surface temperature gradients in that region. When an anticyclonic circulation distorts the upstream trough and zonal flow over the South Pacific, the northerly LLJs tend to reverse in the following days. The dependence of the LLJs upon the upstream wind pattern leads to a speculation that the seasonal variation of the South American LLJs is likely controlled by the seasonal changes of large-scale circulation patterns over the eastern South Pacific. This mechanism also enables us to develop a method for making up to 5-day forecasts of the LLJs based on upstream 700-hPa zonal winds. The cross validation indicates a certain degree of predictability for South American LLJs. The results presented in this paper suggest the importance of monitoring the upstream flow pattern over the South Pacific for the prediction of the South American LLJs. By examining the relations of the LLJs to precipitation, SLP, and the V index, we demonstrated that the LLJs are closely related to circulation changes over other regions. They strongly influence precipitation over both tropical and extratropical South America. A strong northerly LLJ tends to be associated with a weak SACZ. The variation of the subtropical LLJs can also affect the low-level cross-equatorial flow in 1–2 days.

The theory that lee cyclogenesis produces the pressure gradients needed for the development of LLJs is not new. Uccellini (1980) has shown that the upper-tropospheric jet streaks are an important forcing factor in lee cyclogenesis and the development of some of the North American LLJs over the Great Plains region. Recently, Campetella and Vera (2002) and Byerle and Paegle (2002) demonstrated that the LLJs to the east of the Andes can be maintained by the interaction of the basic flow with the topography, using three-dimensional, primitive equation models. Compared to the North American LLJs, South American LLJs are more influenced by the upstream zonal wind in the lower troposphere than in the upper troposphere (not shown). The pressure disturbances associated with lee cyclogenesis are in effect a type of gravity wave that propagates vertically. Their wavelength is proportional to the dimension of the mountain. Since the Andes are relatively narrow in the zonal extent, the induced lee waves are thus short and are likely confined to the lower atmosphere.

Other factors can also influence the South American LLJs. The diurnal variation of the LLJs (Figs. 4d,f) is clearly an indication of the importance of boundary layer processes in modulating the LLJs. The LLJ index is less correlated with the upstream zonal winds in January (not shown) when both Amazon convection and the intensity of the South Atlantic convergence zone (SACZ) are strongest. Hence, we expect that the processes that control the LLJs in austral summer could be significantly different from those in other seasons. How specifically the atmospheric convection over the Amazon and SACZ, and the boundary layer processes affect the summertime LLJs is under investigation. In addition to day-to-day fluctuations, the LLJ index also displays large intraseasonal and interannual variabilities (Figs. 3b,c). Sea surface temperatures (SSTs) in the adjacent oceans could be one of the sources of the low-frequency variability for the LLJs. For example, the eastern Pacific SSTs associated with El Niño–Southern Oscillation (ENSO) may alter the seasonal mean state of the circulation and the frequency of synoptic disturbances over the South Pacific. The interaction of these circulations with the Andes may cause the interannual variation of the LLJs. Since the South American LLJs modulate much of the moisture supply to the La Plata River basin, understanding their interannual variability is of a practical interest to local agriculture and other climate-sensitive sectors of the regional economy.

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