

The South American low-level jet east of the Andes during the 1999 LBA-TRMM and LBA-WET AMC campaign

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[1] The present study describes some observed surface and upper-air features of the low-level jet (LLJ) and southerly jet (SJ). Our results suggest the existence of this low-level circulation to the east of the Andes that transports moisture from tropical South America toward the south during the warm/wet season of 1999. We explore the synoptic variability, diurnal variation, and alternations between LLJ and SJ episodes by using a combination of surface and high-resolution upper-air observations (1 to 8 soundings per day) and global reanalysis. Our results show strong synoptic fluctuations; with the LLJ more frequent than SJs. The LLJ has stronger winds in the afternoon and its core of maximum winds is located between 1600 and 2000 m above the surface. Special observational efforts, such as the pilot balloon sounding network in Bolivia (Pan American Climate Studies Sounding Network [PACS-SONET] program), the Large-Scale Biosphere-Atmosphere (LBA) Experiment-WET Atmospheric Mesoscale Campaign (AMC), and Tropical Rainfall Measuring Mission (TRMM)-LBA in Southwest Amazonia, have provided upper-air information with high temporal and spatial resolution to describe the structure of both the LLJ and the SJ during the January–April 1999 period. *INDEX TERMS*: 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; *KEYWORDS*: convection; jet; Andes; South America

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1. Introduction

[2] An important feature of the low-level circulation in over South America during the warm-wet season is a southward flux of moisture east of the Andes, associated with the deflection of the trade winds by the north-south oriented Andes mountains. This flow from the north is concentrated in a relatively narrow region with strong wind speeds at low-levels - a so-called low-level jet (LLJ) that transports moisture from the Amazon basin toward the agriculturally productive regions of southern Brazil and northern Argentina. During the austral summer, the surface low pressure located near 25°S and 65°W (the “Chaco low”) intensifies due to the positive net radiation. The passage of an upper-level trough over Argentina often leads to the deepening of the Chaco low and an intensification of the northerly flow, favoring the transport of tropical air toward the south and the formation of widespread convective activity [Seluchi and Marengo, 2000].

[3] During the austral winter incursions of polar air toward lower latitudes are linked to cold fronts whose trajectory and movement is favored by the presence of the Andes. These cold surges also occur during the summer, and as the associated cold fronts move northward they merge with the South Atlantic Convergence Zone (SACZ), which becomes more intense. This process is associated with the enhancement of the southerly flow along the Andes, and represents what we refer to as southerly jets (SJ). The importance of these fronts in air mass exchange over subtropical and tropical South America is evident in the precipitation and surface temperature fields [Seluchi and Marengo, 2000; Marengo and Soares, 2002].

[4] Although many important observational features of the LLJ in South America remain unexplored, some earlier studies by Berri and Inzunza [1993], Douglas [1995], Nogués-Paegle and Mo [1997], Douglas et al. [1998, 1999], Paegle [1998], Seluchi and Marengo [2000], Douglas et al. [2000], and Berbery and Collini [2001] have provided preliminary information on the diurnal cycle and horizontal extension of the LLJ. Although Paegle [1998]

and *Saulo et al.* [2000] suggest at least three different LLJs are present around South America: a relatively shallow southerly LLJ off the Chilean coast, a shallow northerly jet centered near the southeast coast of Brazil and Uruguay, and the deep northerly jet to the east of the Andes. This northerly LLJ and the southerly SJ are the focus of this study.

[5] Over North America, the best-documented LLJ occurs over the Great Plains, to the east Rocky Mountains high topography. This LLJ transports moisture from the Gulf of Mexico to the central (and eventually eastern) US, and is, at least indirectly, associated with much of the precipitation over the eastern half of USA during the spring and summer [*Rasmusson, 1967; Wang and Paegle, 1996; Higgins et al., 1997; Barlow et al., 1998; Berbery and Collini, 2001*]. A smaller, weaker LLJ is found over the Gulf of California and is associated with moisture transport from the Gulf of California into northwestern Mexico and the low deserts of Arizona [*Douglas et al., 1993; Douglas, 1995; McCollum et al., 1995; Adams and Comrie, 1998*]. Comprehensive studies on American LLJ's by *Bonner and Paegle [1970]* and *Paegle [1998]* show that the LLJ east of the Andes is stronger during the late afternoon, as opposed to during the nighttime-early morning period, as observed with the LLJ over the US Great Plains [*Higgins et al., 1997*].

[6] In some respects, the Andes and the Rocky Mountains are similar and may be expected to exert similar influences on regional circulations that favor the presence of LLJs. Both mountain ranges extend from the tropics to high latitudes, and block the low-level circulation, producing a channeling effect. However, the Andes are much narrower than the Rockies. LLJs over both continents represent corridors that transport atmospheric tracers (e.g., water vapor) from the tropics and subtropics toward higher latitudes. The transported moisture condenses in a region of ascent downwind of the jet maximum. Here, explosive convection may occur within mesoscale convective complexes (MCCs) [*Velazco and Fritsch, 1987*] that feed upon moisture transported by the LLJ; the LLJ may in turn be modulated by this convection.

[7] Contrasting with what is known about the LLJ over the central US, the east Andean LLJ is a circulation feature whose variability in time and space is relatively poorly understood. These uncertainties include the vertical and horizontal extension of the LLJ, as well the observed diurnal cycle. There are virtually no direct observations of the eastward extent of the LLJ from the Andes into the Amazon region, or if in fact it extends toward southwestern Amazonia, to the east of Santa Cruz (Bolivia) where the few available upper-air soundings have identified the apparent core of the jet. This is partly due to the sparse upper-air sounding network in the region that is not sufficiently dense to resolve the spatial structure of the LLJ. With little observational verification, the NCEP reanalyses have by necessity been taken as a reasonable approximation to the true atmospheric state over this region. Thus, there is a need for high-resolution data in time and space to identify the characteristics and variability of the LLJ east of the Andes, and to determine how far away from the Andes the LLJ extends.

[8] The Large Scale Biosphere Atmosphere Experiment in Amazonia (LBA)-WET Atmospheric Mesoscale Cam-

paign (AMC) was carried out during January–February 1999. This activity coincided with a Tropical Rainfall Measuring Mission (TRMM) validation campaign and took place in southwestern Amazonia in the Brazilian state of Rondônia [*Silva Dias et al., 2002*]. The period of observation varies according to the observation platform but the most complete set of surface and upper-air may be found from 20 January to 24 February 1999.

[9] During the wet AMC a special upper-air observation network, known as the Pan American Climate Studies (PACS) Sounding Network (SONET) [*Douglas et al., 1999; Douglas and Peña, 2000*], was enhanced over the region of Bolivia. These enhanced observations included pilot balloon observations at 5 locations in Bolivia with one of these sites, Santa Cruz, also making radiosonde observations. These observations provide the opportunity to explore the characteristics and variability of the east Andean LLJ and the southerly cold jets.

[10] The main objective of this paper is to describe, from the 1999 observations, the surface and upper-air circulation features associated with LLJ events, provide statistics of LLJs and SJs during January–April 1999, and describe the synoptic variability and alternations between LLJ and SJ episodes. The diurnal cycle of the LLJs and SJs are also described. We explore these features by using a combination of surface and upper-air observations from the TRMM-LBA and LBA-WET AMC campaigns in Rondônia, the PACS-SONET soundings in Bolivia, and surface observations in Bolivia and southern Brazil. However, this paper does not discuss the dynamics of the LLJ, which is matter of ongoing research.

2. Data and Methodology

2.1. Data

2.1.1. LBA-WET AMC

[11] A general description of the LBA-WET AMC experiment and its associated measurements and observational sites is given by *Silva Dias et al. [2001]*. From the LBA-WET AMC data sets, we have used the upper-air observations from the special radiosonde network with 6–8 observations per day in the Brazilian state of Rondônia, and from other radiosonde stations in southern Brazil where 1–2 observations per day were available (Table 1, Figure 1).

[12] G. Fisch (personal communication) provides an analysis of the upper-air soundings during the LBA-WET AMC (Vaisala sondes were used). The Vaisala system uses the standard pressure/height relationships (e.g., measures the pressure and compute height) and the winds are computed each time interval. The Vaisala software has a special function (STATUS) which shows the percentage of good data used for each 10 s of data. For the thermodynamic parameters (pressure, temperature and humidity) this percentage was always higher than 98% while for winds was around 85%. During the LBA-WET AMC, less than 20% of the soundings were discarded or presented defects.

2.1.2. PACS-SONET Enhancement

[13] During late 1998 funding became available from the NASA-LBA Hydrometeorology Program to reestablish atmospheric sounding sites in eastern Bolivia as part of the Brazil-based TRMM-LBA and LBA-WET AMC, and in support of PACS-SONET [*Silva Dias et al., 2002*]. The

Table 1. Location of the Upper-Air and Surface Stations in Brazil and Bolivia Used in This Study^a

Station	Latitude	Longitude	Altitude	Type	Frequency
<i>Bolivia (PACS-SONET)</i>					
Santa Cruz Viru-Viru International Airport	17°45'S	63°08'W	373	Pilot Balloon	2 per day
Trinidad	14°49'S	64°54'W	156	Pilot Balloon	2 per day
Robore	18°19'S	59°45'W	277	Pilot Balloon	2 per day
<i>Southern Brazil (LBA-WET AMC)</i>					
Rolim de Moura	11°42'S	61°46'W	256	Radiosonde	6–8 per day
Reserva Biologica Jaru	10°05'S	61°55'W	289	Radiosonde	6–8 per day
Rancho Grande	10°16'S	62°52'W	178	Radiosonde	6–8 per day
Porto Velho	08°42'S	63°53'W	250	Radiosonde	1–2 per day
Vilhena	12°42'S	60°05'W	320	Radiosonde	1–2 per day
Ji-Parana	10°52'S	61°05'W	190	Radiosonde	1–2 per day
Ariquemes	10°16'S	62°52'W	230	Radiosonde	6–8 per day
Ouro Preto d'Oeste	10°38'S	62°27'W	290	Radiosonde	6–8 per day

^aSee location in Figure 1.

network that finally evolved consisted of one radiosonde station in Santa Cruz (Viru Viru International Airport) and 4 pilot balloon stations elsewhere in Bolivia (Figure 1). Pilot balloon observations were made at Trinidad, Robore, and also at Santa Cruz at ~0630–0700 LST and ~1700–1730 LST each day. The difference between LST and UTC is 4 hours for Bolivia, (e.g., 1200 UTC is equivalent to 0800 LST). These special observations began in January and ended (varying with station) in May 1999. A summary on the type (surface or upper air) and frequency of information for the available sites is given in Table 1.

[14] The PACS-SONET Program was started in 1997, and Santa Cruz in Bolivia was set up as a temporary site for 3 months in 1998, it was not planned to establish a larger Bolivian network until the TRMM-LBA and LBA-WET AMC funding was approved for the radiosonde/pilot balloon sites. So the Bolivian network didn't really exist until 1999. The Bolivian network was designed to monitor the LLJ for TRMM LBA. The network has now continued since LBA because of the interest in maintaining the network from within Bolivia and is part of PACS-SONET, but it originally was set up as a TRMM LBA activity, not as a PACS-SONET activity.

[15] Pilot balloon observations are subject to a variety of errors, especially reading the theodolite angles that can be made during the tracking of the balloon. However, interactive software at PACS-SONET sites permits rapid display and correction of most errors. The most significant source of uncertainty associated with the pilot balloons is related to the fact that balloon tracking is strongly affected by cloudiness and by darkness. In addition, there is an uncertainty in the ascent rate of the balloon that is ~10%, and this translates into a similar uncertainty of the wind speed and altitude of the observation. Despite these limitations pilot balloons are almost always beneficial to a wind analysis at upper levels.

2.1.3. NCEP Reanalysis Data and Other Sources of Data

[16] The daily 925 hPa zonal and meridional winds at 0000, 0600, 1200 and 1800 UTC from the National Center for Environmental Prediction (NCEP) global reanalysis on the $2.5^\circ \times 2.5^\circ$ latitude/longitude grid [Kalnay et al., 1996]

have been used in this study. The model was run at total wave number 64 (T64). The present study utilizes data at 925 hPa with four-times daily fields, interpolating the evenly spaced gridded fields to a Gaussian grid, and then applying a spectral transform determined stream function. From 1979 to 1992, the Australian surface pressure bogus data was inadvertently shifted prior to assimilation by 180° of longitude. Problems associated with this error are believed to be confined to south of 40° S and are most severe during winter [e.g., Garreaud, 1999]. Surface data from selected stations in Bolivia have also been used in this study.

2.2. Methodology: Identification of LLJ and SJ

[17] During the period January–April 1999 episodes of LLJs and SJs were identified based on a combination of surface observations of maximum wind in Bolivia and southern Brazil, and upper-air soundings from Bolivia and southern Brazil. Surface wind speed thresholds were constructed from the maximum wind speed observations (usu-



Figure 1. Location of upper-air stations in Bolivia from the PACS-SONET and Rondônia from the LBA-WET AMC networks. The LBA-WET AMC region is marked. Altitude scale (m) is shown on the lower side of the panel. Legend is on the right hand side.

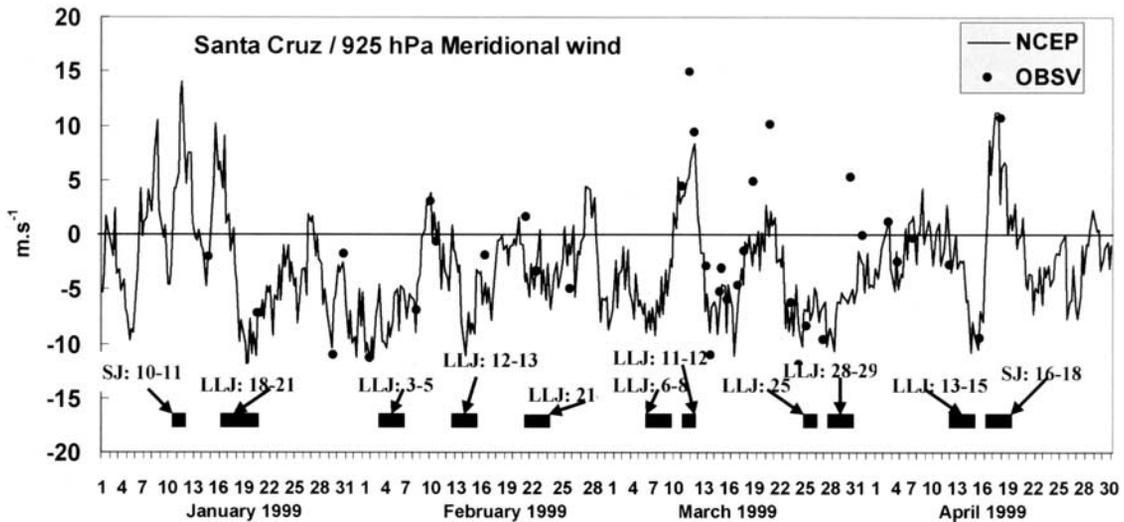


Figure 2. 925-hPa meridional at Santa Cruz during January–April 1999. NCEP reanalysis data for a grid box nearby Santa Cruz is shown in full line. Small full circles show radiosonde observations at Santa Cruz. Time coordinate starts at 0000 UTC of 1 January 1999, and are available every six hours until 30 April 1999. Units are in m/s.

ally afternoon reports) at stations in Bolivia and Brazil corresponding to the upper quartile of the observed speeds. The maximum surface winds reported in the afternoon observations should reflect the wind conditions of the lower tropospheric planetary boundary layer (PBL). During nighttime, the PBL is shallow and the surface winds are often decoupled from the atmospheric flow above due to the strong stability, whereas during the afternoon the PBL is deeper, usually well-mixed, and thus the surface winds reflect better the overlying wind field. However, early morning observations are known to show some intense low-level winds that sometimes represent the continuation of strong LLJ episodes that started the previous day. Time series of NCEP reanalysis 925 hPa winds at a grid point nearest to Santa Cruz have also been used, together with the near surface winds at that site, to explore the synoptic variability and diurnal cycle.

[18] We used the *Bonner criterion 1* applied to the upper-air soundings in Bolivia, and to the NCEP reanalysis for Santa Cruz and Trinidad, Bolivia to identify occurrences of LLJs and SJs. *Bonner* [1968] examined the spatial structure and temporal characteristics of the Great Plains LLJ using three criteria to identify the presence of a LLJ from the vertical profile of wind speed. His criteria 1 specifies that the wind speed profile must have a maximum of at least 12 m/s within 1.5 km of the ground and that the wind speed above the jet must decrease at a rate of at least 6 m/s per km. Also, the level of maximum wind should be at or below the 3 km level. Observations from the PACS-SONET sounding network from Santa Cruz during the 1998 observations [Douglas *et al.*, 1998; Saulo *et al.*, 2000] have identified wind speeds of up to 30 m/s in the northwesterly flow \sim 925 hPa, with speed of \sim 10 m/s at lower levels, and with wind shear of values larger than 6.5 m/s per km below 3 km altitude, which satisfies *Bonner criterion 1*. We will see that in some LLJ episodes at the beginning of March 1999, the wind shear below 3 km reaches \sim 13.5 m/s per km. Even though the

Bonner criterion is arbitrary, it is necessitated by the need to be precise in the statistics.

3. Results

[19] The results discussed in this section should highlight some of the circulation characteristics of the LLJs and SJs and their time variability during January–April 1999. However, the results should not be taken as a definitive study - given the relatively large number of missing observations and the fact that large areas along the jet axis remained poorly sampled.

3.1. Observational Evidence of the LLJ and SJ East of the Andes During Summer 1999

[20] Studies using isolated observations and global reanalyses by *Nogués-Paegle and Mo* [1997], *Saulo et al.* [2000], and *Seluchi and Marengo* [2000] have shown the core of the jet to be located immediately to the east of the Andes at the 925 hPa level, near Santa Cruz and Trinidad in Bolivia (Figure 1). The LBA-WET AMC study area is located to the northeast of the core of the jet. In the following, LLJ and SJ episodes are identified using surface winds only, and then by applying the *Bonner criterion 1* to upper-air soundings from both observations and from the NCEP reanalyses.

3.1.1. Identification of Episodes of LLJ and SJ During January–April 1999 Using Near-Surface Winds

[21] Using surface wind observations alone it is hard to determine how closely the maximum surface winds reflect the atmospheric flow in the lowest kilometer [Paegle *et al.*, 2001]. As noted earlier, the relationship is generally weakest during the nighttime and early morning hours. In any case, “possible candidates” for LLJs and SJs are selected based on strong northerly or southerly maximum daily surface winds during January–April 1999 observed at stations in eastern Bolivia.

[22] Figure 2 shows time series of the 925 hPa meridional wind from the NCEP reanalysis at the grid point nearest

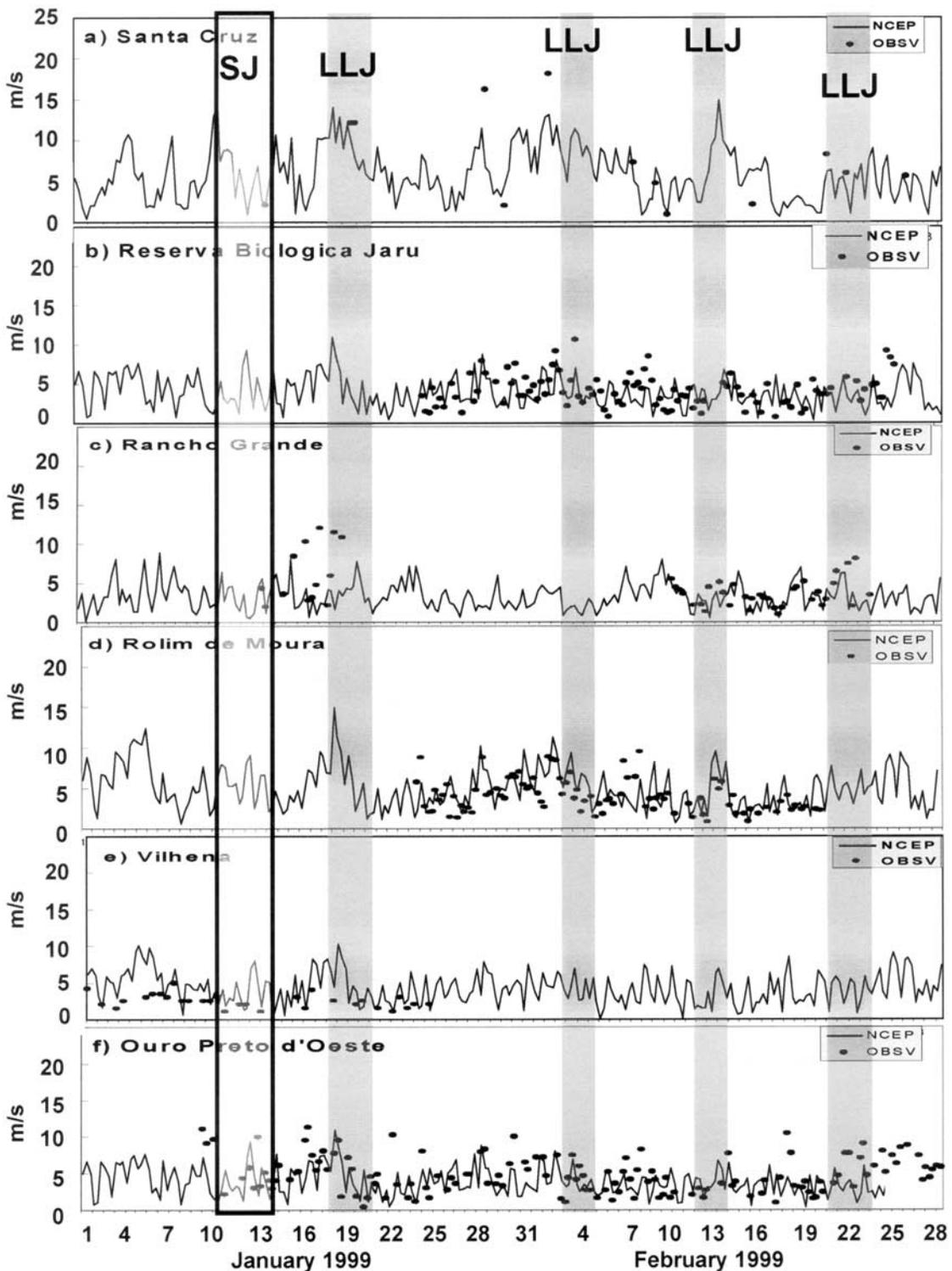


Figure 3. 925-hPa wind speed, derived from radiosonde observations in Rondônia and in Santa Cruz during the January–February 1999 LBA-WET AMC period (m/s). Line shows the NCEP winds while black dots represent observations. (a) Santa Cruz, (b) Reserva Biologica Jaru, (c) Rancho Grande, (d) Rolim de Moura, (e) Vilhena, (f) Ouro Preto de'Oeste. Time coordinate starts at 0000 UTC of 1 January 1999, and are available every 4 hours. LLJ episodes are shown in the gray shaded box and SJ is shown in open box.

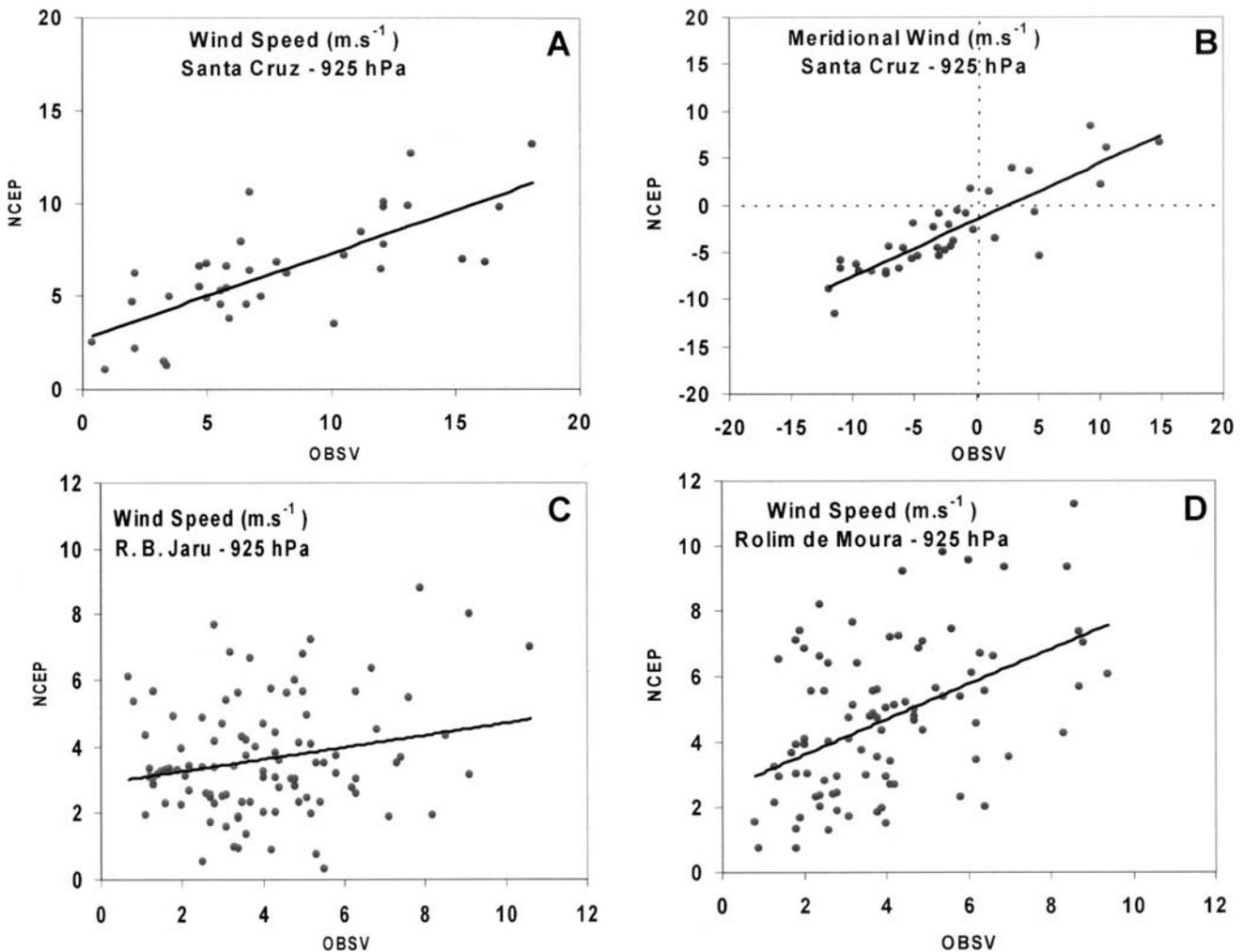


Figure 4. Scatter diagram of observed and NCEP derived 925-hPa winds for the January–February 1999 period: Santa Cruz (a-wind speed, b-meridional wind component), Rolim de Moura (c) and Reserva Biologica Jaru (d).

Santa Cruz, and from the radiosonde and pilot balloon observations at Santa Cruz from January to April 1999. There is reasonable agreement between meridional wind time series from the NCEP reanalyses and the observations, and the agreement is particularly good during LLJ episodes in March and April 1999. It appears that the reanalyses underestimate the intensity of the SJ events, while northerly jets are better reproduced. Similar behavior is detected between observations at Trinidad and meridional winds from the NCEP at a grid point nearest Trinidad (not shown).

[23] Figures 3a–3f shows the observed and the NCEP derived 925 hPa wind speed for a grid point nearest to Santa Cruz and the five sites in Rondônia (Figure 1) during the January–February 1999 LBA-WET AMC period. The large synoptic variability observed at Santa Cruz (Figure 3a) from both the reanalyses and the observations contrasts with a lesser variability at the stations in Rondônia. The lack of continuous observations does not allow for systematic comparison between the observations and the NCEP reanalyses derived near-surface wind between the Bolivian and Rondonian sites. Figure 3 shows that the NCEP reanalyses

exhibit consistency between the timing of the maximum winds at Santa Cruz and in Rondônia during some episodes that appear to be LLJ or SJ. Even though there is a good agreement between reanalyses and observations regarding the changes in the intensity and direction of the winds. The NCEP reanalyses (or any other reanalyses) in the region of the LLJ in South America is based on models that assimilate upper-air observations, which are very scarce on the region of study. It is possible that the reanalyses show only model generated circulation. The comparisons made in Figures 2 and 3 is between point observations and the reanalyses as a grid point of $2.5^{\circ} \times 2.5^{\circ}$ latitude-longitude, and that can explain the under estimation of the observed meridional flow as compared to the reanalyses.

[24] The available observations indicate strong winds with a northerly component in Santa Cruz (18 m/s), Rancho Grande (15 m/s), Vilhena (6 m/s) and Ouro Preto d'Oeste (12 m/s) during the LLJ episode between 17 and 20 January 1999; and strong northerly winds in Santa Cruz (22 m/s), Reserva Biologica Jaru (10 m/s), Rolim de Moura (11 m/s), and Ouro Preto d'Oeste (12 m/s) during the LLJ episode of

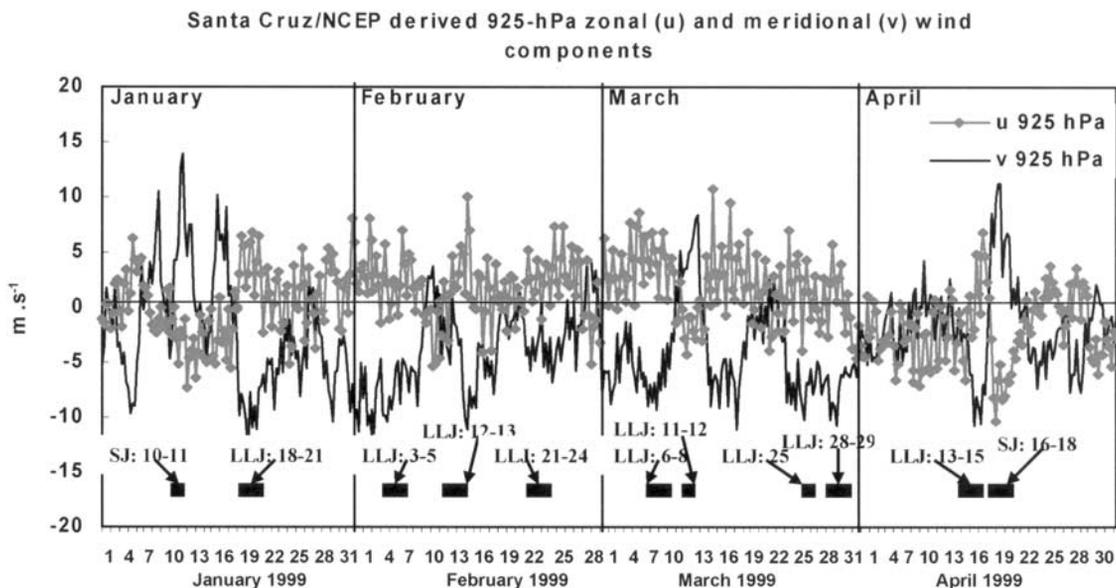


Figure 5. 925-hPa zonal and meridional wind components at Santa Cruz during January–April 1999, as derived from the NCEP reanalysis data for the grid box near Santa Cruz. Thin line with circles shows the zonal wind (u), and thick full line shows the meridional wind (v). Time coordinate starts at 0000 UTC of 1 January 1999, and are available every six hours until 30 April 1999. Units are in m/s. Boxes in the lower side indicate episodes of LLJ and SJ, indicating dates.

3–5 February 1999. However, during the second half of February, strong flow from the South was detected in Ouro Preto d’Oeste (15 m/s) and Reserva Biologica Jaru (13 m/s), while the southerly winds in Santa Cruz barely reached 5 m/s. Although the observed near-surface winds in Rancho Grande (Figure 3c) and Ouro Preto d’Oeste reached 15 m/s, the Bonner criterion 1 wind shear threshold was not met, and thus no LLJ or SJ was classified at those sites, or at the other stations Brazilian stations. Examination of Figure 3 shows good coherence was evident between the occurrence of strong maximum surface winds of northerly component at Bolivian and stations in western Paraguay (not shown). However, the winds in western Paraguay are weaker, with maximum between 6 and 8 m/s, but still maintaining the northerly component (LLJ) or southerly (SJ) components.

[25] The scatter diagrams of Figure 4 provide an objective measure of how close the reanalysis are to observations in Santa Cruz and the Rondonian sites. Figures 4a and 4b show a good fit between the observed wind and especially the meridional wind component at Santa Cruz, while for the Rondonian sites the scatter is considerably larger. Figures 4c and 4d show the large spread between the reanalyses and the observations for Rolim de Moura and Reserva Jaru, while for the rest of sites the pattern is very similar, meaning that there is little correspondence between the observed and reanalyzed winds in Rondonia, while in Santa Cruz the agreement is better.

[26] The possible episodes of LLJ are based on the coherence of occurrence of strong surface speed winds at each station (speeds in the upper quartile) from a northerly direction (330° – 360° – 30°) for at least 75% of six stations in Bolivia. Similarly, episodes of SJ have been determined using the same speed criterion and wind directions between 160° – 180° – 200° degrees. Based on the available surface observations and the consistency between occurrences of

LLJ and SJ events at the six stations, 9 LLJ events and 4 SJ events occurred during the study period.

[27] Figure 5 shows time series of NCEP-derived zonal and meridional wind at 925 hPa, every 6 hours, from 1 January to 31 April 1999 for a grid point nearest to Santa Cruz. Together with Figures 2 and 3, both observations and reanalyses show fluctuations of synoptic time-scale, with 9 peaks of northerly flow larger than 10 m/s, and 3 SJ peaks also larger than 10 m/s, and with the LLJ being more frequent (almost 3 times as common as SJ). Thus there is general agreement between the identification of LLJs and SJs based on the reanalyses and those identified from observations, but there are differences in the details.

3.1.2. Identification of Episodes of LLJ and SJ During January–April 1999 Using Upper-Air Soundings and Bonner Criterion 1

[28] Monthly mean low-level (~ 925 – 850 hPa) wind maps from the NCEP reanalyses show that the strongest winds lie over eastern Bolivia during the months of December to April [Seluchi and Marengo, 2000]. Synoptic variability of the flow could result in the core of the northwesterly winds (or SJ cold surges with southeasterly flow) being found over a broader region, from western Brazil to Paraguay or even northern Argentina or southeastern Brazil. Although northerly jets are more common during spring and summer, there are strong southerly wind events at this relatively low-latitude even during the height of the warm season, although they tend to be more frequent and stronger during the winter season.

[29] Table 2 shows a list of LLJs and SJs identified from the Bonner criterion 1 applied to the radiosonde and pilot balloon data from Santa Cruz and Trinidad. The number of upper-air observations is less than the available surface reports for the January–April 1999, and some of the episodes identified using the surface observations did not

Table 2. Summary of LLJ and SJ Episodes as Deduced From the Bonner Criterion 1^a

Month	Date of LLJ episodes	Dates of SJ episodes
January	18–21	10–14
February	3–5, 7, 12–13, 21–24	
March	1, 6–8, 18, 25, 28–29	11–12
April	13–16	17–18

^aApplied to observed wind profiles in Bolivia (Trinidad, Santa Cruz International Airport, and Robore). Period of study is January–April 1999.

have available upper-air data to compare against. The remarkably strong LLJ/SJ episodes on 15–16/17–19 April 1999 are well detected by both approaches. The synoptic situation during the SJ event in 17–19 April was associated with frost and extreme cooling in states in southern and southeastern Brazil [Satyamurty *et al.*, 2001].

[30] Table 2 shows a list of LLJ and SJ episodes derived from the available upper-air observations at Trinidad and Santa Cruz during January–April 1999, and also for January–March 1988 as comparison for Santa Cruz only. The table was compiled based on the total number of observations (1100 and 1700–2200 UTC); the number of missing observations is also indicated. Some events lasted more than 1 day, but are counted as 1 event. Despite the missing observations, particularly at Santa Cruz in 1999 (Table 2a), we observe a tendency for more LLJ episodes in February and March, while the SJ cold surges episodes (some of them occurring immediately after a LLJ) were relatively more frequent between March and April.

[31] The 1998 observations from Santa Cruz showed that northerly jets were approximately 3 times as common as southerly jets [Douglas *et al.*, 1998], and similar results were found during the summer of 1999 (Figures 2–4), with LLJ episodes approximately 3–4 times more frequent than SJs. Table 3 also shows more LLJs during January–March 1998 as compared to 1999, while SJ are not much different. However, 1998 showed larger number of observations than 1999. Some studies based on regional modeling [Misra *et al.*, 2000] have suggested more LLJ episodes during El Niño year 1997 and 1998 as compared to La Niña year 1999, and we lack of observational evidence to prove that.

Ongoing research show that when the Bonner criterion 1 was applied to NCEP wind profiles at a grid point nearby Santa Cruz during the period December–April season of 1979–2000, more LLJ episodes (35) are detected during 1998 as compared to 12 in 1999. In relation to another El Niño years, 1983 showed 21 LLJ episodes while 1987 showed 63 LLJ episodes. Thus, the NCEP reanalysis alone cannot prove that El Niño years exhibit more LLJ episodes, and systematic observations are needed. The special upper-air soundings during the 1999 LBA-WET AMC campaign were not assimilated by the NCEP operational model to produce the reanalyses.

[32] At Trinidad and Santa Cruz, strong meridional winds are seen during some of the LLJ and SJ episodes identified in Table 2 and plotted in Figures 5a–5d. Northerly meridional winds can reach 18–19 m/s near the 1 km level. The maximum speeds are reached at 1100 UTC, while at 2200 UTC the maximum drops to 12–14 m/s at 2000 m. In most of the LLJ episodes, strong shear (~6 m/s per km) is between 1000 and 3000 m ASL (850 and 700 hPa), and weak winds between 3000 and 6000 m (700–500 hPa). The wind profiles during some of the SJ events can be illustrated by the SJ episode of April 1999 shown in Figures 6c and 6d. The maximum (18 m/s) is somewhat larger than the northerly flow, and is shallower (1000–1200 m) than the northerly LLJ circulation. The moisture content during the evolution of LLJ and the contrast with SJ's related air mass can be seen in Figures 7a–7e for the events of LLJ (one of them followed by a SJ). Even though the maximum winds in Rondônia are lower than those along the core of the jet in Bolivia, it is still possible to detect the contrast of the air masses before and after the passage of a LLJ. The warm humid air before and during the intensification of the LLJ contrasts with the relative drier air once the LLJ weakens. This contrast is more pronounced in Santa Cruz. After the LLJ episode in April 1999, the SJ episode is characterized by cooler and drier air at lower levels (Figures 7d–7e).

3.1.3. Diurnal Variability of LLJ and SJ

[33] Times series of meridional wind (Figure 5) exhibits the mean diurnal cycle from the 4-times-a-day NCEP reanalysis. It shows maximum wind speed at 850 hPa

Table 3. Number of LLJ and SJ episodes for January–April 1999^a

	January	February	March	April
<i>Trinidad 1999</i>				
LLJ episodes	2	5	8	2
SJ episodes	–	–	1	1
Total observations	36	56	41	54
Total missing days	18	–	7	1
<i>Santa Cruz Viru-Viru International Airport 1999</i>				
LLJ episodes	3	6	3	1
SJ episodes	–	–	1	1
Total observations	13	25	18	12
Total missing days	17	10	14	22
<i>Santa Cruz Viru-Viru International Airport 1998</i>				
LLJ episodes	11	7	3	ND
SJ episodes	–	3	–	ND
Total observations	40	31	14	ND
Total missing days	6	7	18	ND

^aBased on all observations available from the pilot balloon and radiosonde observations at Trinidad and Santa Cruz (PACS-SONET). Upper-air wind data for January–April 1998 are also included for comparison. No observations were available during 1998 for Santa Cruz.

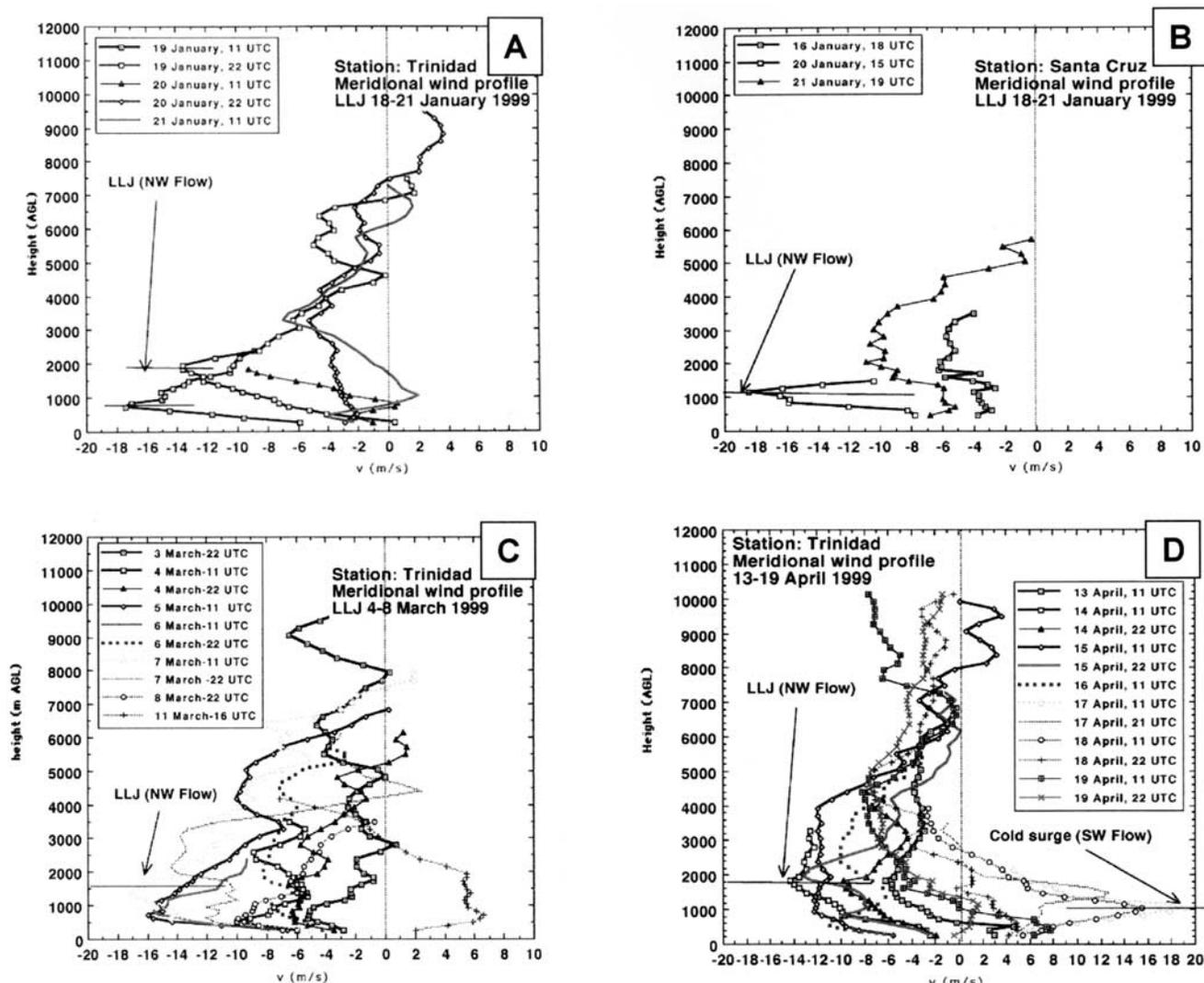


Figure 6. Meridional wind profiles at the PACS-SONET sites in Bolivia during some LLJ and SJ episodes. 18–21 January 1999 and Trinidad (a) and Santa Cruz (b) 4–6 March 1999 at Trinidad, (d) 13–19 April 1999 at Trinidad. Altitude above ground level is in meters, and horizontal scale is speed (m/s). Altitude of the axis of the LLJ is shown with a horizontal line. Dates and times are shown in the box inside the panels, showing the date and time (UTC).

between 0600 and 1200 UTC (0200–0800 LST) and minimum around 1800 UTC (1400 LST). The analysis of wind profiles during the summer-autumn of 1998 [Douglas *et al.*, 1998] identifies a deep and late afternoon (rather than shallow and early morning) wind maximum at Santa Cruz. Douglas *et al.* [1998] show, based on eta model results, a marked diurnal cycle with an evening maximum (around 0000 UTC). This is in general agreement with studies based on one year of sounding data by Inzunza and Berri [1991] in Salta, Argentina (25 S, just east of the Andes). However, these authors found that at Resistencia, situated ~600 kilometers to the east, the opposite temporal distribution was evident. However, it is possible that the limited number of observations from Santa Cruz used by Douglas *et al.* [1998] from the January–April 1998 period do not reflect climatology, since they consisted of only 90 pilot balloon observations made over 70 days.

[34] The results of this study (Table 3) based on a limited amount of data (115 days, 68 observations in Santa Cruz

among pilot balloons and radiosondes and 187 observations in Trinidad) show strongest winds during the afternoon, in agreement with findings from Douglas *et al.* [1998] for the January–April 1998 season. The analysis of SJ episodes during the 1999 summer-autumn season suggests an earlier maximum, between 0000 and 0600 UTC. However, it should be stressed that with twice-a-day data we cannot put high confidence on these results to infer the diurnal cycle of the LLJ or SJ more frequent and systematic observations are clearly desirable.

4. Summary and Conclusions

[35] Routine global analyses suggest the existence of a lower-tropospheric northerly LLJ to the east of the Andes, extending from the Amazon Basin and sometimes reaching the Argentine plains. This LLJ serves as a moisture corridor between tropical South America and the fertile lands of the Paraná-La Plata River basin. This flow is similar to the much

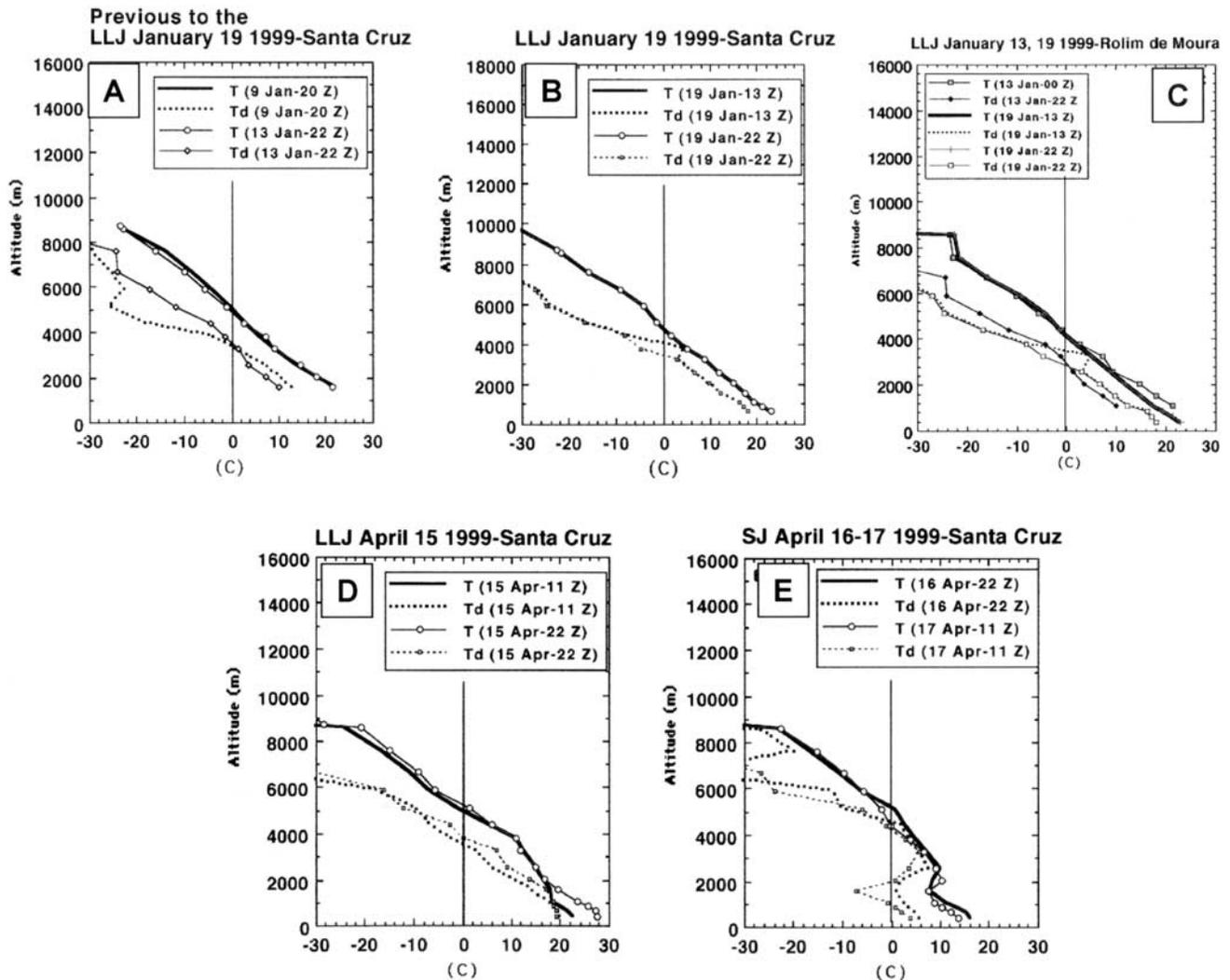


Figure 7. Air and dew point temperature profiles during some LLJ and SJ episodes in Santa Cruz (a, b) and Rolim de Moura (c) during the LLJ episode of January 1999, and in Santa Cruz (d, e) during the LLJ/SJ episode of April 1999. Altitude above ground level is in meters, and horizontal scale is temperature (C). Dates and times are shown in the box inside the panels, showing the date and time (UTC).

more extensively studied warm season LLJ over the Great Plains of North America. While LLJs are associated with warm and moist flow from the northwest, cold air incursions, referred to here as SJs, bring relatively cool and dry air from the southeast. In-situ observations have been scarce, due to the sparse sounding network in this region, and thus there is a need to quantify aspects of the jet, such as the location and intensity of the jet core, the vertical structure of the current, and the contrast of moisture associated to the meridional air mass exchange associated to LLJ and SJ. Global NCEP reanalysis data, together with twice-daily pilot balloon and radiosonde observations were made in Bolivia during the summer of 1999, supporting the TRMM-LBA observational program in southwestern Brazil. These data sets, together with surface observations from Bolivia were used to describe LLJ and SJ events. From these observations, an account for episodes of LLJ and SJ events was developed for the region during January–April 1999. Comparison with observations in 1998 in Santa Cruz, and with NCEP reanalyses data, suggest an

interannual variability in the intensity and frequency of the LLJ and SJ.

[36] The strength of the LLJ has been identified from the maximum winds at 850 hPa from the NCEP reanalyses over eastern Bolivia, and the observing sites of Santa Cruz and Trinidad that have been assumed to be located among the core of the jet. The Bonner criterion 1 was used to identify LLJ and SJ episodes from the upper-air soundings in Bolivia and southern Brazil, as well as from the NCEP reanalyses in locations nearest to the sounding sites. These profiles, as well as meteorological reports during the LBA-WET AMC and the PACS-SONET observations revealed LLJs and SJs with strong synoptic variability during the summer of 1999.

[37] After analyzing soundings at the Bolivian sites, approximately 17 episodes of LLJ and 2 episodes of SJ were identified. In comparison, more episodes of LLJ (21) were identified during 1998 at Santa Cruz. However, this cannot be generalized to other El Niño or La Niña (see *Misra et al.* [2000] for some regional model experiments on the effect of El Niño 1998 in the frequency/intensity of LLJ). On

some occasions, the LLJ extends into southern Amazonia, as shown by the wind profiles in Rondonia. However, the Bonner criterion applied to the Rondônia soundings did not recognize any LLJ structure even though the surface winds from northwest and reaching sometimes more than 15 m/s. Finally, the moisture content of the air masses is a key distinct issue of both LLJ and SJ, and the contrast between warm-humid northerly air and the cool-drier southerly flow is observed in the radiosonde-based analysis of dew point and air temperature for sites in Bolivia and Rondonia.

[38] The timing of the maximum intensity of the LLJ agrees with findings by Douglas *et al.* [1998] in the previous year. It is clear that in order to obtain more reliable results on the diurnal cycle of the LLJ, more frequent and systematic observations per day are needed.

[39] Our results are based only on the analysis of data from summer and autumn of 1999, and reference to previous work in 1998. These two years constitute two extremes of interannual variability, being 1998 an El Niño year and 1999 a La Niña year. Thus, these results should not be taken as “climatology” of LLJ and SJ east of the Andes. The discrepancy between the diurnal cycle derived from the surface/upper-air observations and the NCEP reanalyses, indicates the need for more observations; a more accurate evaluation of the diurnal cycle will be accomplished through a dense network of observations at least 4–6 times per day, and this is the subject of the upcoming South American Low-Level Jet Experiment (SALLJ), planned for the austral summer 2002–2003 as part of the Variability of South American Monsoon Systems (VAMOS) Research Program [Paegle *et al.*, 2001].

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References

- Adams, D., and A. Comrie, The North American Monsoon, *Bull. Am. Meteorol. Soc.*, **78**, 2197–2213, 1998.
- Barlow, M., S. Nigam, and E. Berbery, ‘Evolution of the North American Monsoon’, *J. Clim.*, **11**, 2238–2257, 1998.
- Berbery, E. H., and E. A. Collini, Springtime precipitation and water vapor flux convergence over southeastern South America, *Mon. Weather Rev.*, **128**(5), 1328–1346, 2001.
- Berri, G. J., and B. Inzunza, The effect of the low-level jet on the poleward water vapor transport in the central region of South America, *Atmos. Environ., Part A*, **27**(3), 335–341, 1993.
- Bonner, W. D., Climatology of the low level jet, *Mon. Weather Rev.*, **96**, 833–850, 1968.
- Bonner, W. D., and J. Paegle, Diurnal variations in boundary layer winds over the south-central United States in summer, *Mon. Weather Rev.*, **98**, 735–744, 1970.
- Douglas, M. W., The summertime low-level jet over the Gulf of California, *Mon. Weather Rev.*, **123**, 2334–2347, 1995.
- Douglas, M. W., and M. Peña, The Pan American Climate Studies Sounding Network (PACS-SONET) recent history and planned improvements, in *Extended Abstr. of the 6th Int. Conf. on South. Hemisphere Meteorol. and Oceanogr.*, Apr. 3–7, 2000, Santiago, Chile, pp. 258–259, Am. Meteorol. Soc., Boston, 2000.
- Douglas, M. W., R. Maddox, K. Howard, and S. Reyes, The Mexican monsoon, *J. Clim.*, **6**, 1665–1667, 1993.
- Douglas, M. W., M. Nicolini, and C. Saulo, Observational evidences of a low level jet east of the Andes during January–March 1998, *Meteorologica*, **3**, 63–72, 1998.
- Douglas, M. W., M. Nicolini, and C. Saulo, The low-level jet at Santa Cruz, Bolivia during January–March 1998, pilot balloon observations and model comparisons, in *Extended Abstr. of the 10th Symp. on Global Change Stud.*, January 10–15, 1999, Dallas, Tex., pp. 223–226, Am. Meteorol. Soc., Boston, 1999.
- Douglas, M. W., M. Peña, and R. Villarpando, Special observations of the low level flow over eastern Bolivia during the 1999 atmospheric mesoscale campaign, in *Extended Abstr. of the 6th Int. Conf. on South. Hemisphere Meteorol. and Oceanogr.*, Apr. 3–7, 2000, Santiago, Chile, pp. 157–158, 2000.
- Garreaud, R. D., Cold air incursions over subtropical South America: Mean structure and dynamics, *Mon. Weather Rev.*, **128**, 2544–2559, 1999.
- Higgins, W., Y. Yao, E. Yartosh, J. Janowiak, and K. Mo, Influence of the Great Plains Low-Level Jet on summertime precipitation and moisture transport over the Central United States, *J. Clim.*, **10**, 481–507, 1997.
- Inzunza, B. J., and G. J. Berri, Comportamiento del viento y transporte de vapor de agua en la baja troposfera en el norte de Argentina, *Meteorologica*, **17**–25, 1991.
- Kalnay, E., et al., The NCEP/NCAR 40-year reanalyses project, *Bull. Am. Meteorol. Soc.*, **77**, 437–471, 1996.
- Marengo, J., and W. Soares, Episódios de Jatos de Baixos Niveis aoleste dos Andes durante 13–19 de abril 1999, *Rev. Bras. Meteorol.*, **17**(1), 35–52, 2002.
- McCollum, D., R. Maddox, and K. Howard, Case study of a severe mesoscale convective system in central Arizona, *Weather Forecast.*, **10**, 643–655, 1995.
- Misra, V., P. Dirmeyer, B. Kirtman, H. Huang, and M. Kanamitsu, Regional simulation of interannual variability over South America, *COLA Tech. Rep.* **85**, 42 pp., COLA, Calveston, Md., 2000.
- Nogués-Paegle, J., and K.-C. Mo, Alternating wet and dry conditions over South America during summer, *Mon. Weather Rev.*, **125**, 279–291, 1997.
- Paegle, J., A comparative review of South American low level jets, *Meteorologica*, **3**, 73–82, 1998.
- Paegle, J. N., et al., American Low Level Jets. A Scientific Prospectus and Implementation Plan, Draft, CLIVAR, 120 pp., Dep. of Meteorol., Univ. of Utah, Salt Lake City, 2001.
- Rasmusson, E. M., Atmospheric water vapor transport and the water balance of North America, I, Characteristics of the water vapor flux field, *Mon. Weather Rev.*, **95**, 403–426, 1967.
- Satyamurty, P., J. Bustamante, M. Bottino, M. C. Seluchi, L. G. Lourenço, and Gonçalves, An early freeze in southern Brazil in April 1999 and its CPTEC NWP guidance, *Meteorol. Appl.*, **v. 8**, 1–16, 1999.
- Saulo, C., M. Nicolini, and S. C. Chou, Model characterization of the South American low-level flow during the 1997–98 spring-summer season, *Clim. Dyn.*, **16**, 867–881, 2000.
- Seluchi, M., and J. Marengo, Tropical-mid latitude exchange of air masses during summer and winter in South America: Climatic aspects and extreme events, *Int. J. Climatol.*, **20**, 1167–1190, 2000.
- Silva Dias, M., et al., Clouds and rain processes in a biosphere atmosphere interaction context in the Amazon Region, *J. Geophys. Res.*, **107**, 10.1029/2001JD000335, in press, 2002.
- Velasco, I., and J. M. Fritsch, Mesoscale convective complexes in the Americas, *J. Geophys. Res.*, **92**, 9591–9613, 1987.
- Wang, M., and J. Paegle, Impact of analysis uncertainty upon regional atmospheric moisture flux, *J. Geophys. Res.*, **101**, 7291–7303, 1996.

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