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Chaco low-level jet events characterization during the austral summer season

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[1] Previous studies showed a relationship between convection maxima and the convergence of vapor flux over southeastern South America. *Nicolini and Saulo* [2000] explored the hypothesis of an intensification of this mutual dependency during the Chaco Jet events. They defined these events as extreme cases of low-level jets east of the Andes that penetrate southernmost to 25°S using ETA operative products during the 1997–1998 austral warm season. The interest of the present paper centers on the climatic characterization of the Chaco Jet events (CJEs) and the possibility of researching this hypothesis using the European Centre for Medium-Range Weather Forecasts reanalyses (ERA), which cover a 15-year period (1979–1993). The CJEs represent a subensemble of low-level jet events east of the Andes that are infrequent in the ERA data set. Their duration varies from 1 to 10 days, more frequently extending from 1 to 5 days. The outstanding features of the circulation and the thermodynamic field that represent this ensemble are a maximum contrast of air masses in a latitude close to 39°S, the presence of a trough centered on 70°W within a baroclinic wave train penetrating from the Pacific Ocean, and a maximum of heat and moisture over northen Argentina and Paraguay. During the CJEs, there is an important flux of moisture and convergence at low and mid levels that is about 10 times more intense than the summer mean. The intensity found in the water vapor flux anomaly reinforces the importance of studying these episodes for the purpose of determining the water balance over southeastern South America. The statement that the CJEs represent an important characteristic of the southeastern South American climate is founded on the fact that, although the CJEs only represent 17% of the austral summer days, they account for a significant fraction of the precipitation (a maximun of 55%) over northeastern Argentina. However, it is indispensable to contrast these results with future field experiments to test the hypothesis addressed in this paper. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3364 Meteorology and Atmospheric Dynamics: Synoptic-scale meteorology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); *KEYWORDS:* South American low-level jet, humidity transport, precipitation impacts

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1. Introduction

[2] Understanding the mechanisms that participate in the hydrological balance of the South American basins is important. One of the two main basins in South America is Del Plata basin. The Paraná, Uruguay, Paraguay, and Del Plata Rivers and their tributaries constitute this basin (identified in Figure 1). Identifying the predominant mechanisms for the transport of heat and water vapor to a region that partially encompasses the Del Plata basin is of special interest inasmuch as the latter contains one of the largest economic and human settlements in South America. This region is commonly referred to as southeastern South America (SEAREA) (denoted by a rectangle in Figure 1).

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[3] The penetration of air masses of tropical origin into midlatitudes is frequently related to the Chaco and northwestern Argentine depression [*Schwerdtfeger*, 1976] and the South Atlantic Subtropical Anticyclone. Between both systems a northerly wind establishes a channel that affects the hydrological balance of Del Plata basin mainly during spring and summer seasons. The precedent for the existence of this 850 hPa jet current dates back to *Virji* [1981], who identified it by studying satellite data during 6 days in January. Also, *Li and Le Treut* [1999] highlighted the role of this channel studying strong events of southward transient component of the meridional moisture transport for summer and winter.

[4] Figure 2 shows the mean outgoing longwave radiation (OLR) field for the summer months (December, January, and February) from 1979 to 1993. This field

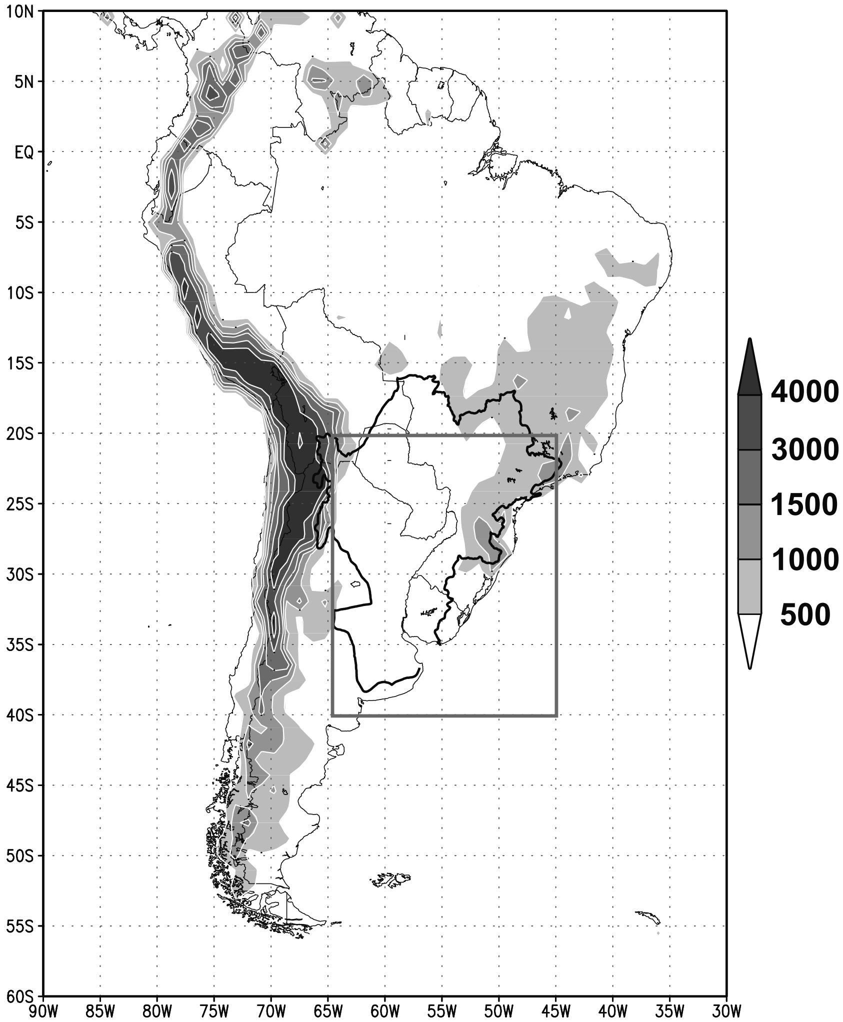


Figure 1. Topography over South America. Contours correspond to terrain elevations of 200, 400, 800, 1600, and 3200 m. Rectangle denotes the southeastern South American region.

reveals two areas with maximum values, associated with the maximum intensity of deep convection previously pointed out by other authors. The most extensive of these is over the Amazon, and the second one is over the central Andean summits and slopes centered on 12°S, 72°W. The South Atlantic Convergence Zone (SACZ) shows a characteristic South American cloud pattern during the summer that has been studied by several authors [e.g., *Liebmann et al.*, 1999; *Nogués-Paegle and Mo*, 1997] and that is represented by a slight extension toward the southeast of the OLR minimum that intersects the coastline at 25°S. On the other hand, the convection associated with the mesoscale convective complexes during the summer months [*Velasco and Fritsch*, 1987] in the continental region that encompasses Paraguay, northeast and central Argentina, southern Brazil, and Uruguay does not appear clearly in the mean field.

[5] Figure 3 illustrates the presence of intense convection in the SEAREA. Figure 3a shows the daily variations of OLR anomaly averaged between 62° and 57°W (the westernmost part of the SEAREA) for January 1987. The area between latitudes 20°S and 35°S, which comprises central and northern Argentina and Paraguay, shows days with extreme negative OLR in the first fortnight of January and others, in the second fortnight, when the absence of convection predominates. Figure 3b shows the variations of meridional water vapor transport at 850 hPa ($q*v$) for the same period averaged over the same longitudes. Figure 3b suggests a relation between negative OLR anomalies with southward penetration of vapor transport, particularly during the first 10 days of January. The absence of cloudiness in the region between 20°S and 35°S latitude is associated with southerly maximums of $q*v$ which were most evident on 25 January. In turn, *Salio et al.* [2000] investigated the relationship between precipitation extremes and the vertically integrated moisture flux divergence. The observed positive anomaly precipitation and the occurrence of an important convergence of vertically integrated moisture flux in the SEAREA were related in January 1987, while the contrary happened in January 1985.

[6] Following modified *Bonner*'s [1968] criteria 1 and using the products of the regional ETA model with high horizontal and vertical resolution operationally run during the spring and summer of 1997–1998, *Saulo et al.* [2000]

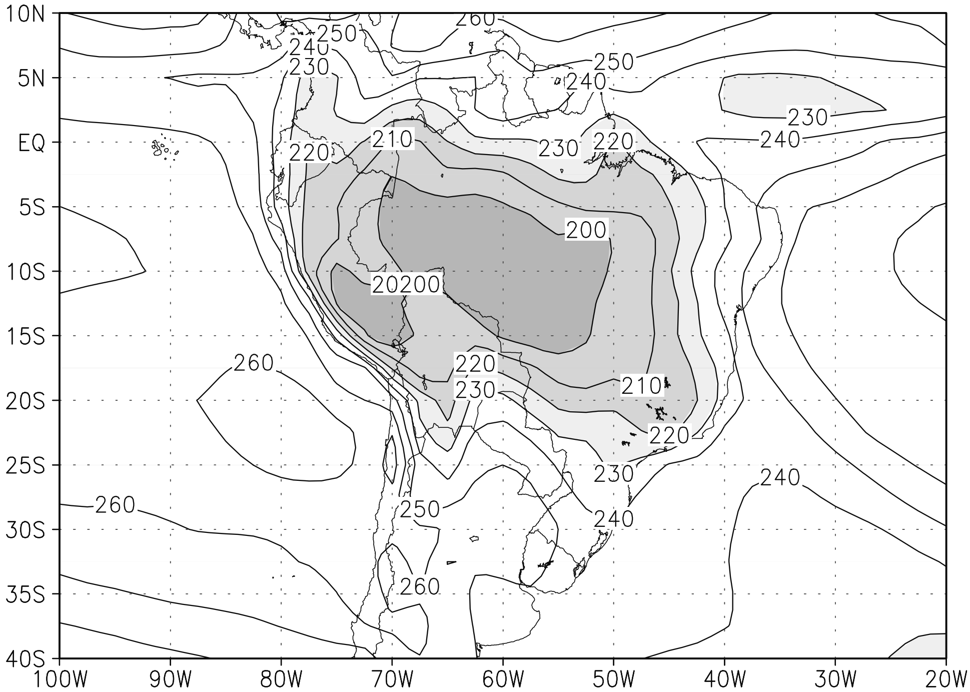


Figure 2. Mean outgoing longwave radiation during the austral summer (DJF). Contour interval is 10 W m^{-2}; values lower than 230 W m^{-2} are shaded.

identified the days in which the criteria verified the existence of low-level jets (LLJs) over South America. They confirmed the existence of a LLJ immersed in a northerly current east of the Andes during this particular season and progressed in characterizing its mean scale (around 300 km cross-stream), structure, and intensity. Also they show its role as a moisture conveyor from the Amazon Basin to subtropical latitudes. An estimation of the water vapor budget over a region similar to SEAREA, which includes the Del Plata basin, with the inclusion of data from both observed and modeled precipitation, characterized this area as a wet atmospheric moisture sink. However, it should be emphasized that this study encompassed a particular warm period, when El Niño had a strong signal, and may not be representative of the "climatological" LLJ behavior.

[7] Assuming a relationship between convection maxima and the convergence of vapor flux, it would be worthwhile to explore the hypothesis of an intensification of this mutual dependency in the SEAREA. *Nicolini and Saulo* [2000] explored this hypothesis using a subensamble of low-level jet cases previously identified by *Saulo et al.* [2000]. These cases are characterized by an anomalous southward penetration compared with warm season 1997–1998 mean position and are denoted as "Chaco Jets" because of the name of the geographical region that encompasses them. *Nicolini and Saulo* [2000] found that the Chaco jet cases seem to integrate the warm stage of a synoptic-scale interaction between midlatitudes and the tropics along the eastern slope of the Andes, whereas the cold stage has been studied by *Garreaud* [2000]. Evidence of enhanced precipitation over SEAREA during Chaco events in the 1997–1998 warm season supports the mentioned hypothesis but clearly needs a longer time period analysis in order to determine its impact upon regional climate.

[8] The interest of this research centers on extending the study of the hypothesis assumed by *Nicolini and Saulo* [2000] to a longer period of time using the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA) to produce a comprehensive "climatology" of the CJEs and to document its mean structure and synoptic-scale dynamics.

[9] The LLJ phenomena have been extensively studied (see *Stensrud*'s [1996] summary of the subject). *Anderson and Arritt* [2001] investigated the benefits of using National Centers for Environmental Prediction (NCEP) reanalyses to correctly represent the location and spatial field of the frequency of LLJ occurrence in the Great Plains. They point out the risk of using data analyzed at a time when the field is heavily influenced by the general circulation model (GCM) that is employed to produce those analyses. For this reason they compare the fields analyzed at 0600 and 1200 UTC with the data obtained with wind profilers, and they show that the LLJ cases, which complied with Bonner's criterion 1, were correctly simulated during the Northern Hemisphere summer. However, they find greater deviations between the wind profiler data and the analyzed wind fields at 0600 UTC, and these increase with the more intense LLJ events. These results reinforce the assumption that reanalyses must be employed with caution particularly when the number of observations is relatively scarce. The region of South America spanned by the Chaco jets has a poor observational network, and, in this sense, caution must be exercised. At the present time, reanalyses constitute the only set of complete data to attempt the mean characterization of the CJEs proposed in this paper.

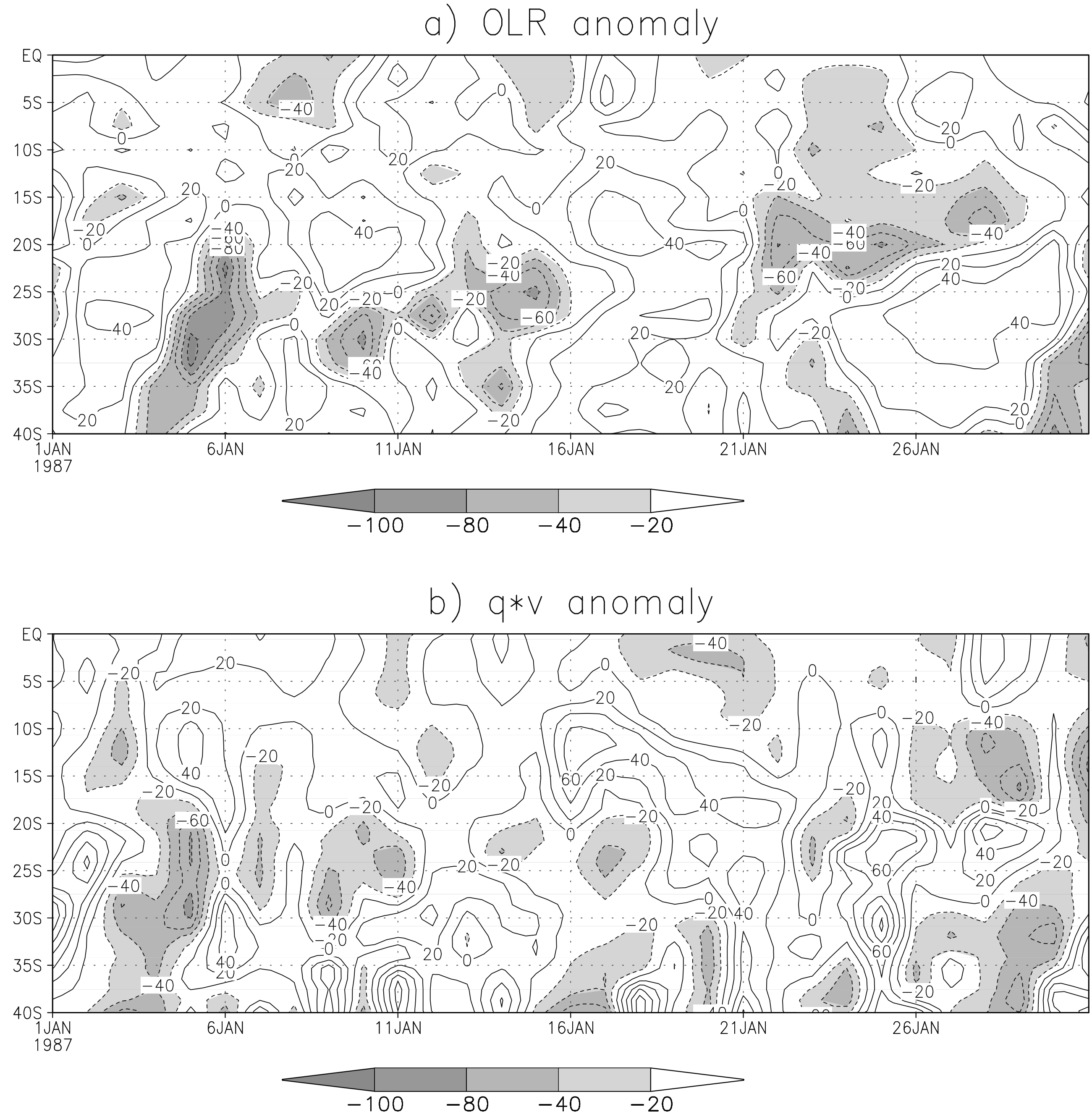


Figure 3. (a) Latitude-time diagram of outgoing longwave radiation anomalies (departure from January 1987 mean) averaged between 57°W and 62°W for January 1987. Contour interval is 20 W m^{-2}; values lower than -20 W m^{-2} are shaded. (b) As in Figure 3a but for meriodional moisture flux anomalies at 850 hPa. Contour interval is 20 g m kg^{-1} s^{-1}; values lower than -20 g m kg^{-1} s^{-1} are shaded.

[10] The paper is organized as follows. Section 2 describes the data employed and a brief description of some aspects of the climate of South America. Section 3 describes the criteria for selection employed. Results are presented in sections 4 and 5, and the conclusions are summarized in section 6.

2. Data Sets and Summer Characterization

[11] The ERA reanalyses used for this investigation are available for the four synoptic hours on an N80 Gaussian grid with a resolution of approximately 1.125° × 1.125° latitude-longitude and 17 vertical levels of pressure. The present analysis is based on the 1979–1993 time period during the Southern Hemisphere summer of December, January, and February (DJF). A complete description of the data is given by *Gibson et al.* [1996, 1997].

[12] Mean fields throughout the summer and during the particular events studied were averaged over the 4 hours of reanalyses except when the diurnal oscillations were analyzed.

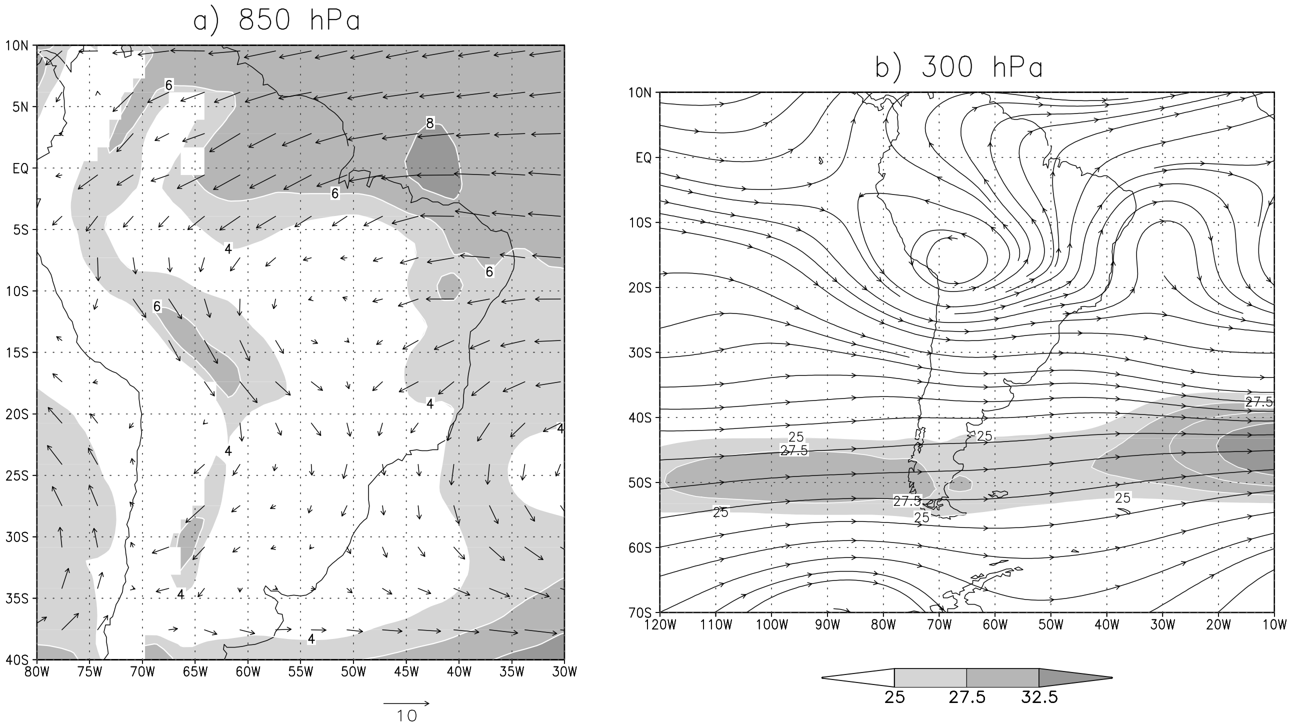


Figure 4. (a) Mean summer low-level wind (vectors) and wind speed (values higher than 4 m s^{-1} are shaded) at 850 hPa. Mountain areas higher than 1500 m are masked. (b) Mean summer high-level streamlines and wind speed (values higher than 25 m s^{-1} are shaded) at 300 hPa.

[13] The second data set consists of daytime and nighttime fields of outgoing longwave radiation with a 2.5° × 2.5° latitude-longitude resolution for the same period, measured by polar-orbiting satellites and produced by the National Oceanic and Atmospheric Administration (NOAA) and the National Centers for Environmental Prediction (NCEP), freely available in the Climate Diagnostic Center home page [*Liebmann and Smith*, 1996].

[14] The daily-accumulated precipitation data used in this paper were obtained from an extensive network of rainfall stations in Argentina, Brazil, Paraguay, and Uruguay. The data were interpolated into a 2° latitude-longitude grid applying the kriging method.

[15] Numerous papers that studied the climate of South America employed NCEP reanalyses. [e.g., *Nogués-Paegle and Mo*, 1997; *Garreaud and Wallace*, 1998; *Garreaud*, 1999]. We shall describe briefly the mean fields of the variables obtained by ERA that are of interest for the purposes of the present paper in order to ascertain the summer characteristics.

[16] The mean flow at 850 hPa during the summer (Figure 4a) is characterized by strong east-northeast trade winds close to the Equator which veer to the northwest as they approach the Andes, producing a maximum of the meridional wind component toward the south close to Santa Cruz de la Sierra (STA) in Bolivia. Another northerly maximum occurs at approximately 25°S, 40°W associated with the subtropical Atlantic Anticyclone.

[17] The high-level circulation (Figure 4b) depicts the presence of the Bolivian High [*Lenters and Cook*, 1997; *Figueroa et al.*, 1995] centered approximately on 15°S, 67°W. Westerly winds predominate toward the south of the continent.

[18] There are strong diurnal cycles in winds at 850 hPa (Figure 5) on the South American continent, mainly south of 15°S. There is an anticyclonic rotation east of the Andes that is consistent with *Blackadar*'s [1957] mechanism. This circulation generates a maximum of the v wind toward the south at 0600 UTC, at which time the surface frictional component is negligible and wind acquires a supergeostrophic component. This accords with the findings of *Nicolini et al.* [1987], who employed a boundary layer model to analyze the diurnal oscillations of the horizontal and vertical motion resulting from the daily cycle of the boundary layer processes in an ideal situation without environmental flow and a real situation with a northerly flow. They found that, in the absence of an environmental flow, the resulting northerly flow, forced by the drive on the land slope and the coastal inhomogeneities, responds to a radiation cycle and results in a nocturnal northerly circulation east of the Andes. This diurnal oscillation is even more intense in synoptic situations with environmental flows from the north. Reanalyses show upslope circulation at 0000 UTC (8:00 P.M. local time), while the downslope circulation takes place at 1200 UTC (8:00 A.M. local time) driven by a bouyant force over a sloping terrain, which are approximately consistent with the hours following maximum heating and cooling times, respectively, of the planetary boundary layer in the region of the Andes. The field of wind anomalies at 0600 UTC is consistent with the analysis of *Nicolini et al.* [1987] inasmuch as it demonstrates a

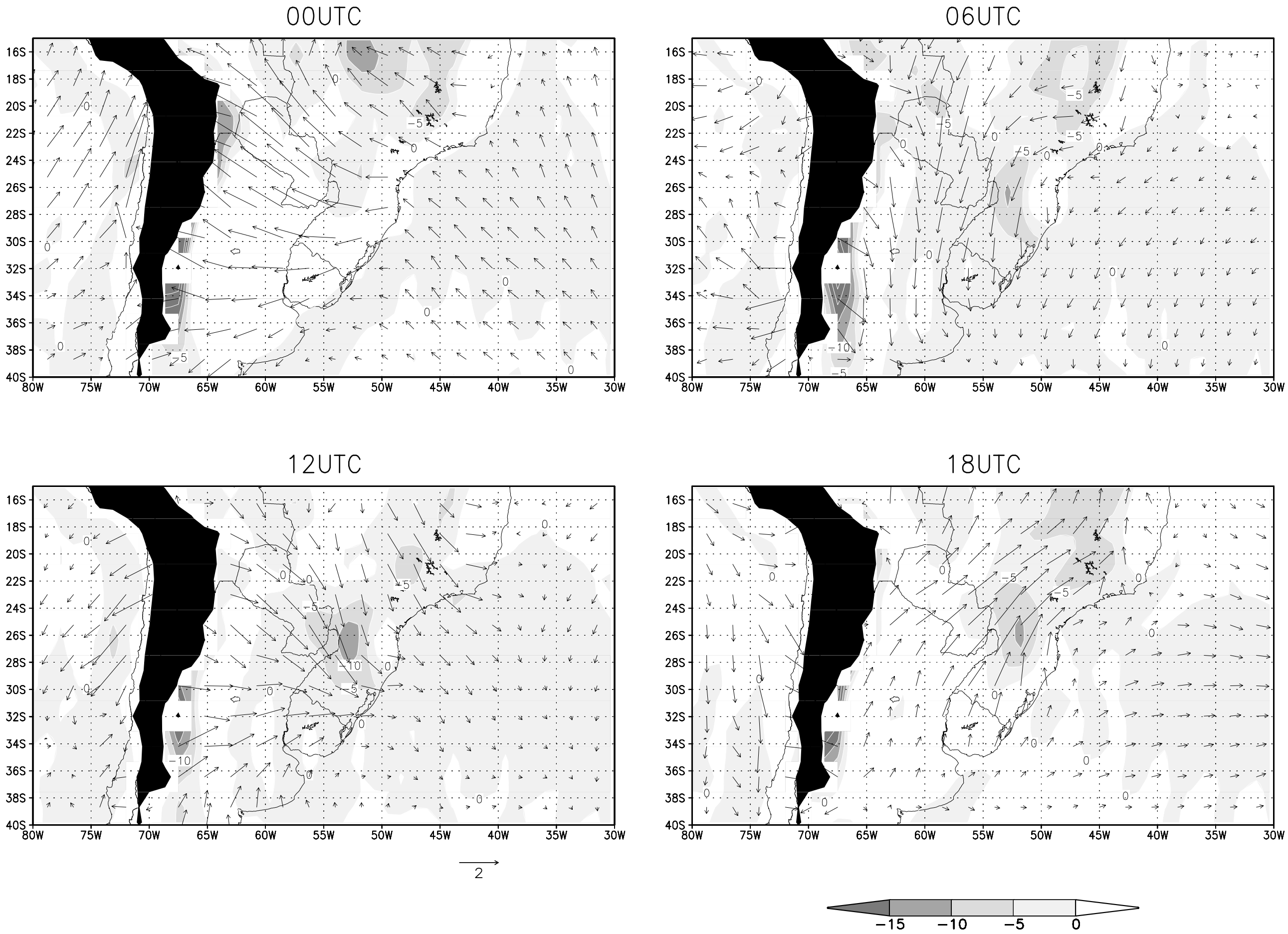


Figure 5. Diurnal evolution of mean summer wind anomalies (vectors) and moisture flux divergence anomaly (in g kg^{-1} s^{-1}) at 850 hPa. Graphics only show convergence regions. Mountain areas higher than 1500 m are masked.

northerly supergeostrophic component in northern and central Argentina. In relation to the wind field anomaly, Figure 5 shows a water vapor divergence anomaly field at 850 hPa at each respective hour in which a water vapor convergence is observed over northeastern Argentina, southern Brazil, and Uruguay with extreme values at 1200 UTC.

Table 1. Number of Occurrences of Chaco Jet Days for the ERA Data Set

Summer	December	January	February	Total
1979	–	0	3	3
1980	12	3	3	18
1981	4	6	6	16
1982	7	3	8	18
1983	9	4	2	15
1984	2	8	14	24
1985	3	0	7	10
1986	7	5	2	14
1987	7	9	7	23
1988	4	11	0	15
1989	2	5	3	10
1990	0	12	2	14
1991	9	5	4	18
1992	8	1	6	15
1993	11	2	0	13
1994	4	–	–	4
Total	89	74	67	230
Percent	19	16	15	17

3. Chaco Jet Events Definition

[19] The Chaco jet day was defined by adjusting the criterion determined by *Nicolini and Saulo* [2000] for the vertical and horizontal resolution of the ERA reanalyses

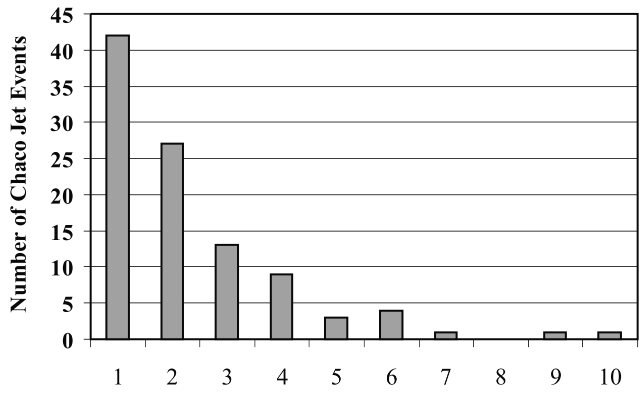


Figure 6. Number of Chaco Jet events (CJEs) of a given length (days).

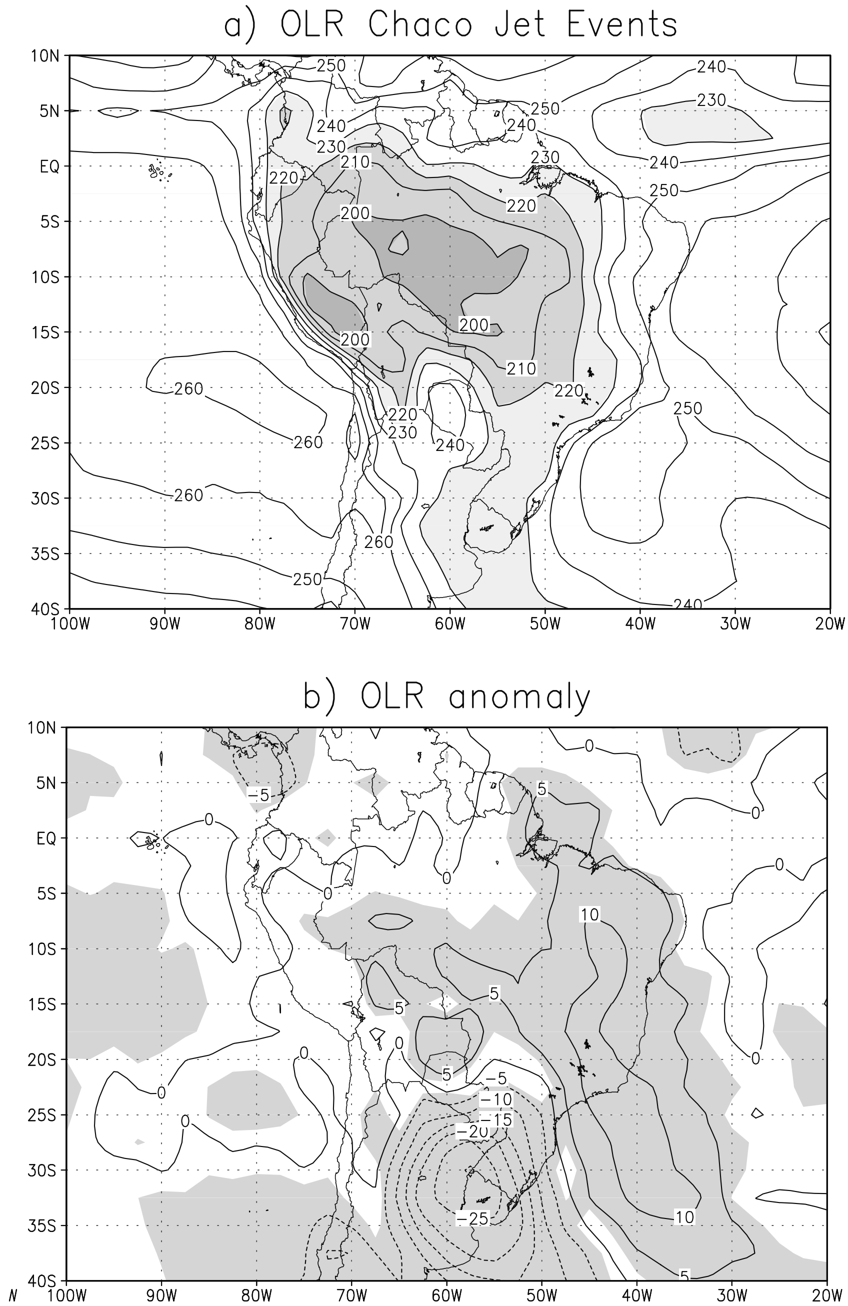


Figure 7. (a) Outgoing longwave radiation composite for CJEs contoured every 10 W m^{-2}. Values lower than 230 W m^{-2} are shaded. (b) Outgoing longwave radiation composite anomalies for Chaco Jet events. Light shading indicates the 95% significance level.

with the objective of studying the extreme events of moisture transport from the tropical latitudes southward to the central plains of Argentina, Paraguay, southern Brazil, and Uruguay.

[20] This criterion requires that at least one of the four synoptic hours confirm the following: (1) Maximum wind intensity ($|V|$) at 850 hPa immediately east of the Andes must be equal to or greater than 12 m s^{-1} and must originate in tropical latitudes and extend to 25°S. (2) The difference of the wind speed between 850 to 700 hPa must be larger than or equal to 6 m s^{-1} in some part of the region enclosed by the 12 m s^{-1} isotach. (3) The meridional component must be northerly and greater than the zonal component (u) in the entire region enclosed by the 12 m s^{-1} isotach. This condition is established in order to exclude events that take place prior to the passage of a frontal system at 25°S where the zonal wind component is strongly predominant.

[21] Table 1 indicates the number of Chaco days obtained by using the above mentioned criterion during DJF. The Chaco jet event (CJE) is defined as the occurrence that complies with the criterion for more than 1 consecutive day. Table 1 shows that there were a total of 230 Chaco jet days during the summer season of the time period 1979–1993 which represent a total of 17% of the days examined. Chaco jet days are more frequent in December and January, while in February the incidence is slightly reduced. The CJEs last

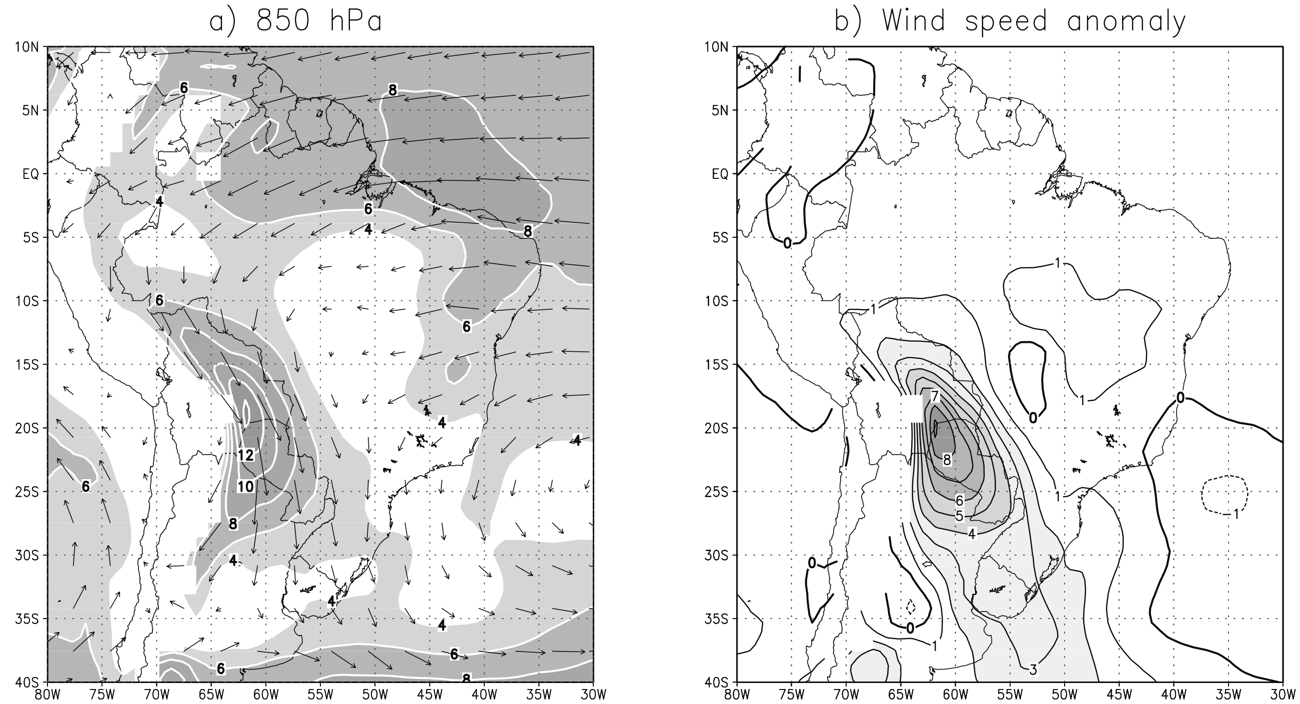


Figure 8. (a) Wind (vector) and wind speed (contoured every 1 m s^{-1}, values greater than 4 m s^{-1} are shaded) composite at 850 hPa for CJEs. (b) Wind speed composite anomalies at 850 hPa for CJEs are contoured every 1 m s^{-1}; values greater than 4 m s^{-1} are shaded.

1–10 consecutive days (Figure 6) and represent 94% of all the events that last 1–5 days.

[22] It is interesting to describe the synoptic-scale characteristics associated with CJEs. In order to filter the daily wind oscillation demonstrated in section 2, the mean daily field for the CJE is calculated by means of the four available hours. In order to guarantee the independence of the events it is necessary to calculate the mean of the variables on the days that compose each CJE. The anomalies of the CJEs are determined with respect to the average of the 15 summer seasons of the ERA. We computed a two-tailed 95% significance level, using the *t* student test, for the composite anomalies for all displayed fields and include them for reference in the figure captions with the purpose of ascertaining the level of significance of the anomalies we studied.

[23] In view of the fact that in the following sections the daily mean fields will be considered, in the present section we emphasize that all the Chaco jet day maxima occurred at 0600 or at 1200 UTC. In no case was the Chaco jet day identified at 0000 UTC or 1800 UTC because, as explained in section 2, the northerly v has a minimum at 0000 UTC and 1800 UTC hours. For this reason the daily mean fields of the CJE have a lower intensity than that required by the adopted criterion.

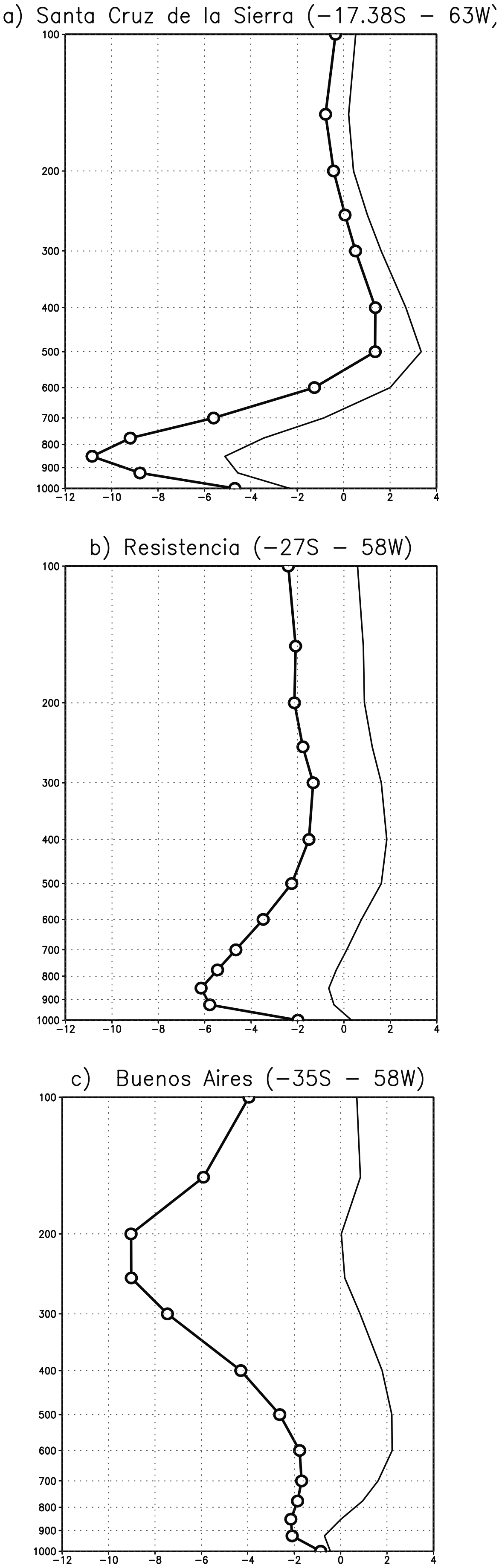
[24] The mean field of the OLR for the CJEs (Figure 7a) shows the presence of a corridor for OLR minima lower than 230W m^{-2} centered on 58°W and which extends from 25°S to 40°S. The OLR anomaly field (Figure 7b) shows the presence of a dipole in which convection increases on the zone over 30°S, 58°W and weakens over the region centered on 20°S, 42°W and oriented in a northwest-southeast direction. *Nogués-Paegle and Mo* [1997] found a seesaw pattern in OLR anomalies over the same region while discussing wet and dry conditions over subtropical South America in relation to weak and enhanced SACZ.

[25] The minimum magnitude in the OLR anomalies surpasses 10% of the value of the mean field, and its location coincides with the region where the mesoscale convective complexes significantly contribute to the summer precipitation. This evidence motivates the characterization of the CJE in relation to its associated water vapor flux.

4. Characteristics of the Chaco Jet Events

[26] The mean wind field at 850 hPa (Figure 8a) for the CJEs shows a strong southward flow that penetrates northern Argentina and southern Brazil. This type of configuration given by the low-level wind responds to the expected field because of the selection criterion established for the CJE. There is a wind speed maximum close to the STA zone that extends up to 30°S with values higher than 4 m s^{-1}. The anomalies for wind speed at 850 hPa (Figure 8b) show positive values that extend southward from 14°S with a maximum close to the Bolivia-Paraguay border obtaining values higher than 9 m s^{-1}. It is interesting that the trade winds over northern South America show no difference between the events studied and the mean field.

[27] The v wind vertical profile (Figure 9a) at a grid point close to STA shows an intensification of the jet-like profile for the CJEs with respect to that corresponding to the mean field. It shows a decrease in velocity from 12 m s^{-1} between 500 and 850 hPa, while the summer mean field shows a difference of 9 m s^{-1} between the same levels. This type of



profile is still present during the occurrence of CJEs farther south at a point close to Resistencia (SIS) which is weakly evident in the mean field (Figure 9b). Though in Buenos Aires this jet profile is not observed, it is interesting that v in the CJEs is greater than v in the mean field throughout the column and especially at 200 hPa.

[28] The geopotential field and its anomaly at 1000 hPa (Figures 10a and 10b) show an important augmentation of the low-pressure system extending east of the Andes from 17°S to 35°S, which intensifies the northerly winds east of the low-pressure zone. Figure 10b shows the largest deepening values of the low pattern that occurs at approximately 25°S, 65°W. This feature is consistent with the deepening of the Northwestern Argentinean Low, centered around 30°S, 66°W, that develops previously to the maximum of a CJE (M. Seluchi et al., The northwestern Argentinean low: A study of two typical events, submitted to *Monthly Weather Review*, 2002). The minimum of geopotential anomaly centered on 50°S, 58°W together with a maximum located southwest of Chile jointly integrates a baroclinic wave pattern which penetrates from the Pacific Ocean.

[29] Figure 11 shows the streamline field and geopotential anomaly at 300 hPa. There is a slight eastward shift of the Bolivian High during the CJEs (Figure 11a) and a westward shift of the northeastern Brazilian trough with respect to the mean summer field (Figure 4b) that increases the southerly flow east of the Bolivian High. The intensification of the upper level jet at the leading side of the midlatitude trough centered on 70°W should be noted. The presence of this trough, evident during the CJEs, is also denoted by the wave pattern present in the geopotential anomaly field (Figure 11b). The position of the anomalies with respect to the field at 1000 hPa shows a westward displacement that corroborates the baroclinicity of the system. It is possible to characterize a vertical structure of the divergence field for the CJEs through a vertical section of the divergence anomaly at 30°S (Figure 12). There is a center of positive anomaly divergence at high levels of the atmosphere that is associated with the leading side of the trough. This positive divergence overlies a negative anomaly associated with the same system that extends to approximately 500 hPa. An intensification of this convergence anomaly is observed with a minimum value less than -0.2×10^{-5} s^{-1} below 850 hPa, associated with the decelerating area downwind of the low-level jet near 58°W.

[30] There is a dominating heat and specific humidity maximum centered on 30°S, 58°W in the anomaly field of equivalent potential temperature at 850 hPa for the CJEs (Figure 13). An intensification of air mass contrast (around 14°C) between this maximum and a minimum centered on 42°S, 68°W during CJEs is clearly evident in Figure 13 and denotes the presence of a cold front oriented northwest-southeast recognizable at 39°S. This is also evident in the anomaly field for the 1000/500 hPa layer (not shown). This

Figure 9. (opposite) Meridional wind profile composite for Chaco Jet events (open dot line) and summer (solid line) at (a) Santa Cruz de la Sierra, Bolivia (17.38°S, 63°W); (b) Resistencia, Argentina (27°S, 58°W), and (c) Buenos Aires, Argentina (35°S, 58°W).

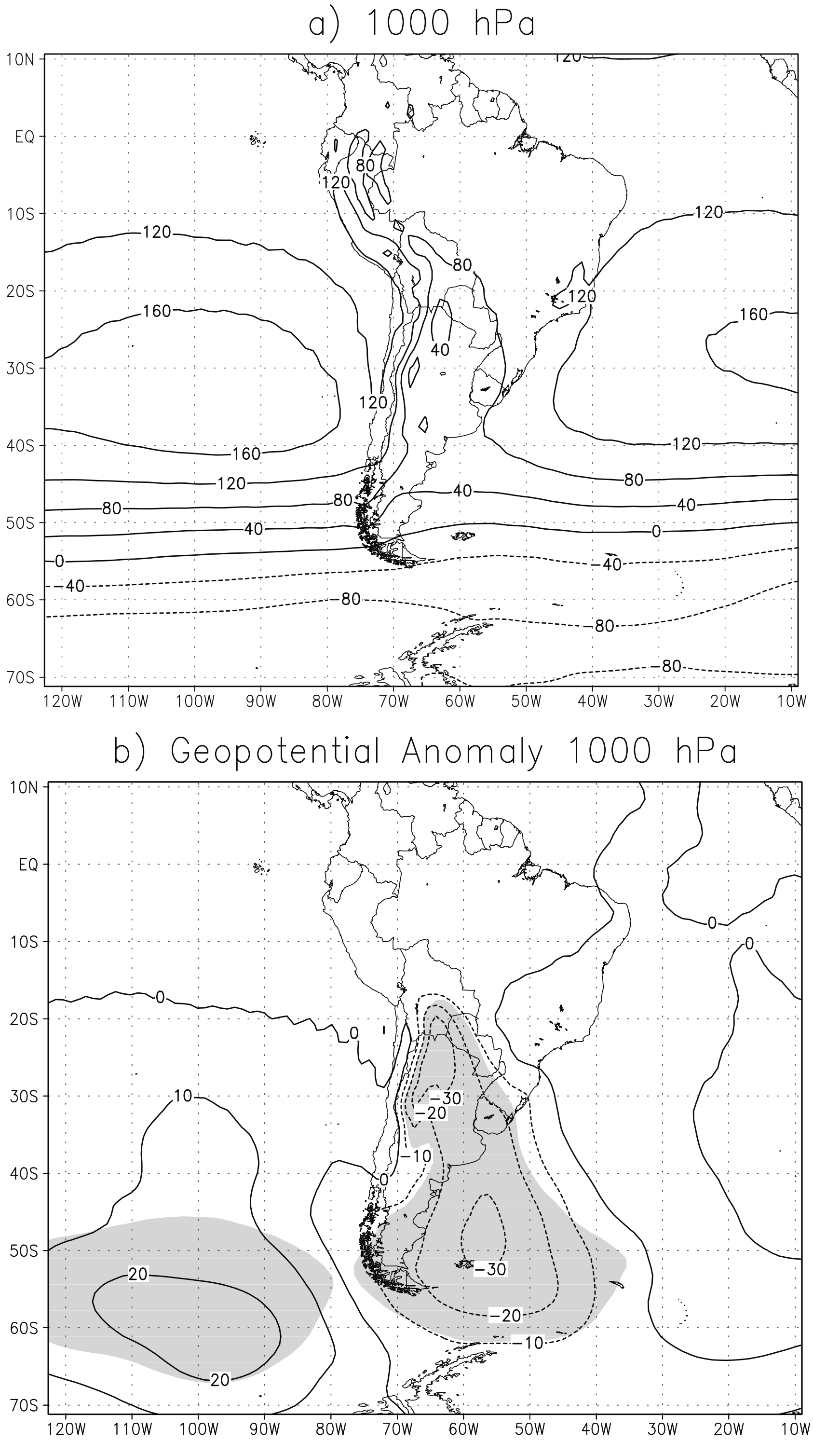


Figure 10. (a) Geopotential height composite for CJEs at 1000 hPa contoured every 40 mgp. (b) Geopotential height composite anomalies for CJEs at 1000 hPa contoured every 10 mgp. Negatives values are dashed. Light shading indicates the 95% significance level.

field is similar to that shown by *Garreaud* [2000] in his Figure 6 for the days prior to the intrusion of cold air in the midlatitudes during the summer.

[31] Figure 14 shows a vertical section of equivalent potential temperature and its anomaly at 30°S for the purpose of analyzing the convective instability of the region. The mean field for the CJEs shows a layer of convective instability east of the Andes that maximizes at 66°W, lowering from around 600 hPa to 700 hPa as it approaches the Atlantic. The anomaly field shows a deep maximum east of the Andes that involves the entire troposphere.

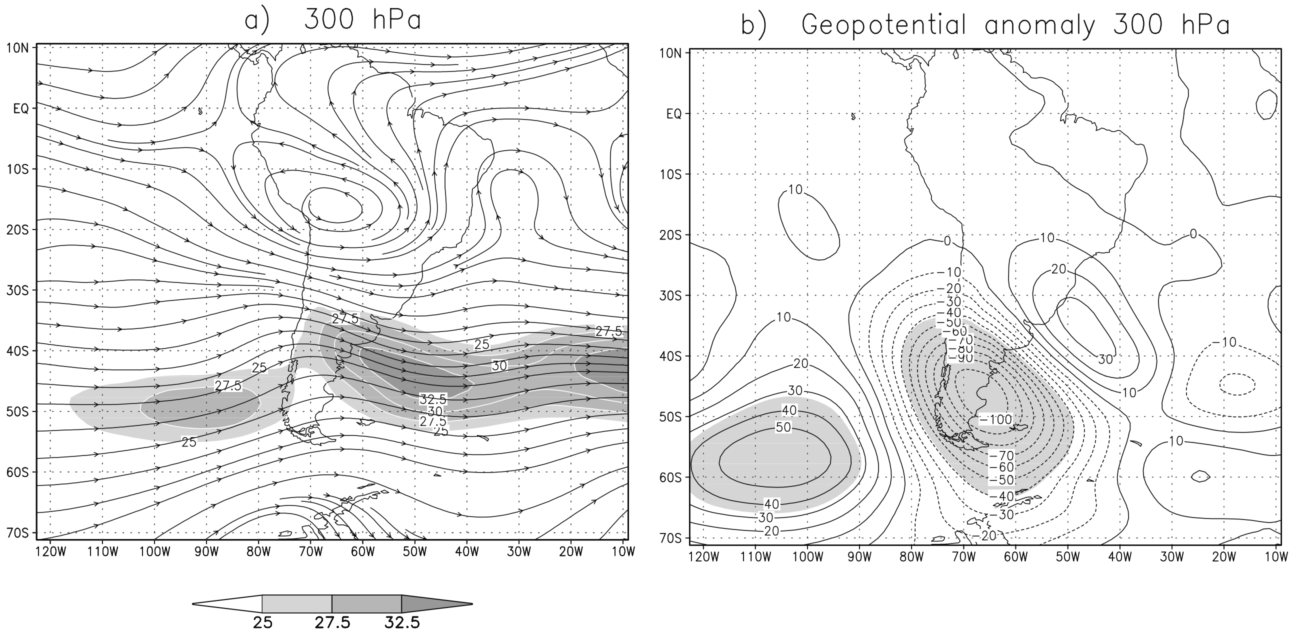


Figure 11. (a) Streamlines and wind speed (contoured, values greater than 25 m s^{-1} are shaded) composite for CJEs at 300 hPa. (b) Geopotential composite anomalies for CJEs at 300 hPa contoured every 10 mgp. Negatives values are dashed. Light shading indicates the 95% significance level.

[32] The pattern of vertical and horizontal divergence east of the Andes together with the convective instability favor rising motion in this region is consistent with the negative extremes of the OLR anomalies (Figure 7b).

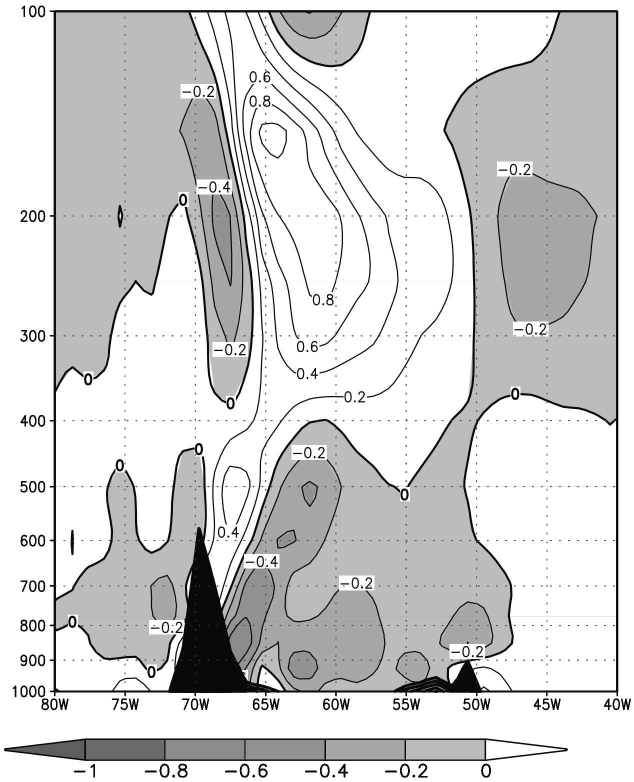


Figure 12. Longitude-pressure section of divergence composite anomalies for CJEs at 30°S. Topographic cross section is also included.

5. Water Vapor Transport Associated With Chaco Jet Events

[33] It is relevant to quantify the incidence of the CJEs as an efficient agent to transport water vapor from tropical to extratropical latitudes. In this section we shall examine

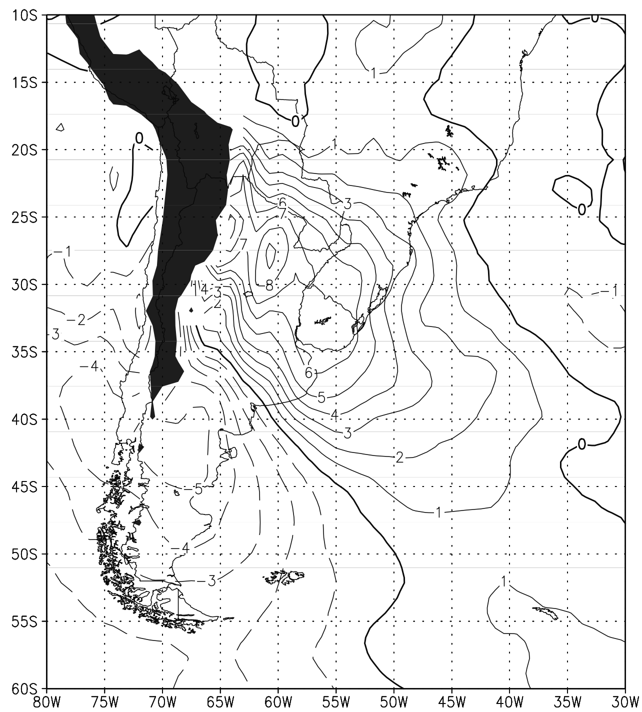


Figure 13. Equivalent potential temperature composite anomalies for CJEs at 850 hPa contoured every 1°C. Negative values are dashed.

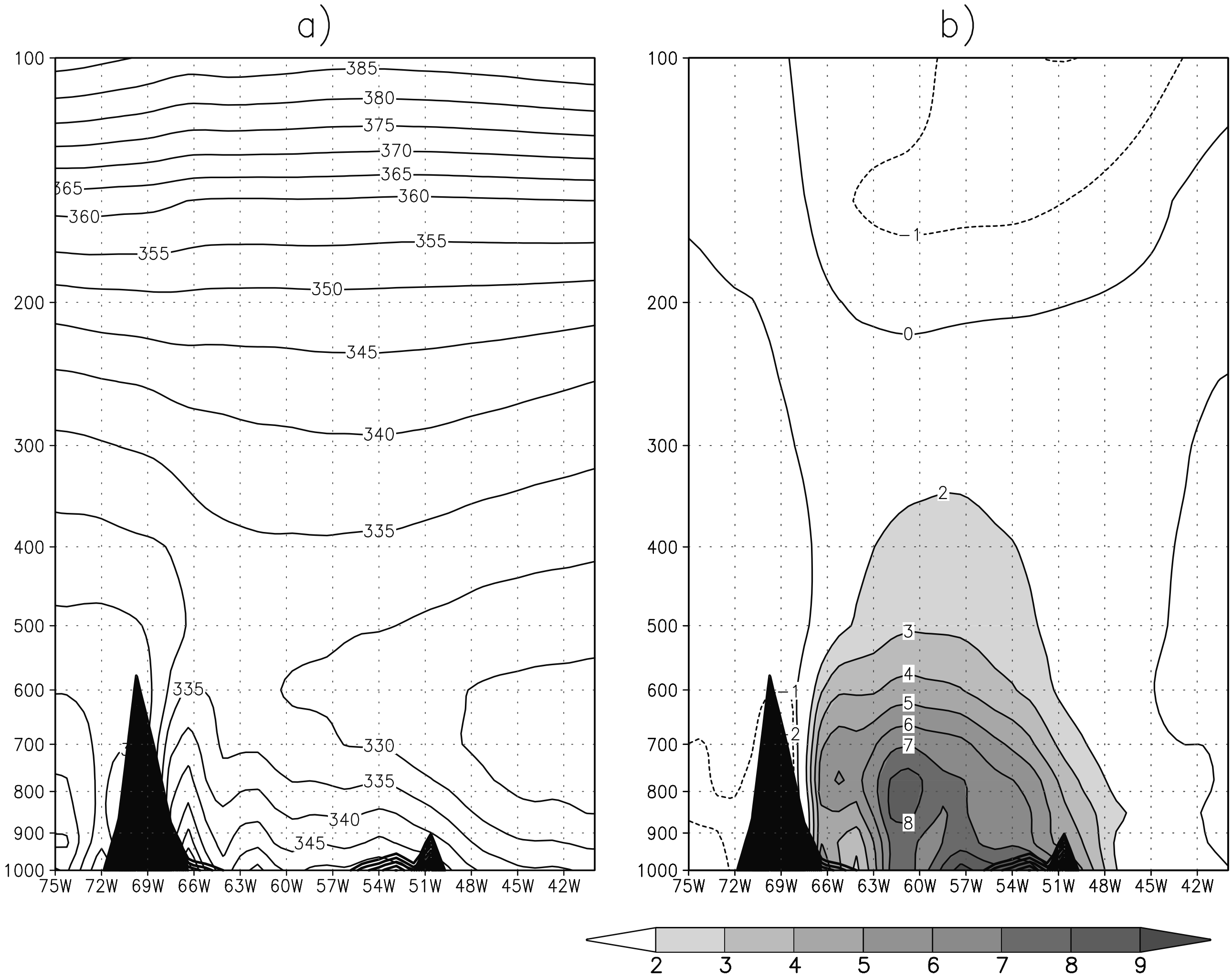


Figure 14. Longitude-pressure section of (a) equivalent potential temperature composite for CJEs at 30°S (contoured every 5°C) and (b) same as Figure 14a but for composite anomalies. Topographic cross sections are also included.

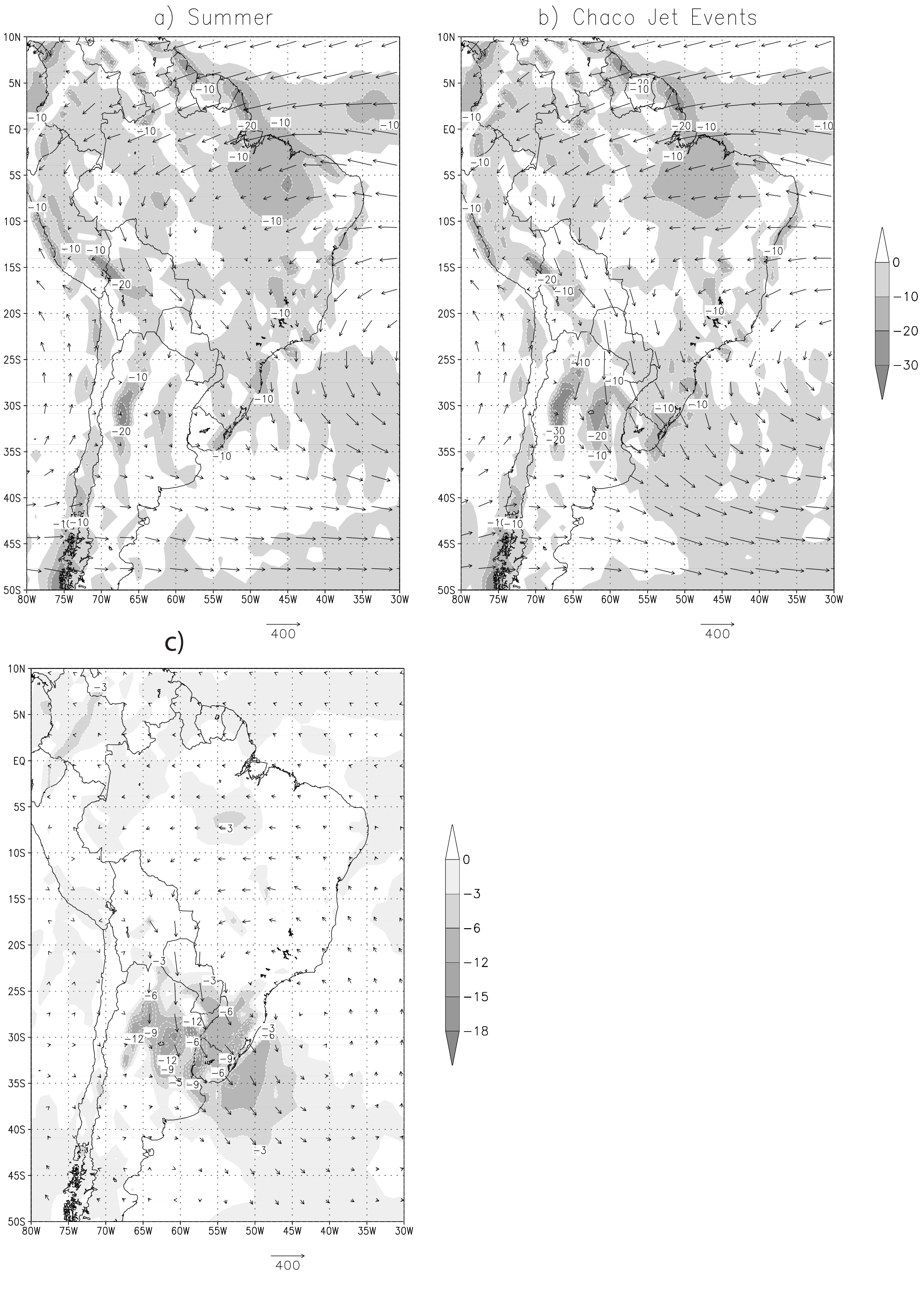
the vertically integrated moisture flux (**Q**), which is defined as

$$\mathbf{Q} = \int_{Pt}^{Ps} \frac{q\mathbf{V}}{g} dp, \qquad (1)$$

where q is the specific humidity, **V** is the wind vector, and g is gravity. Vertical integration is calculated by means of a trapezoidal integral from 1000 hPa (Ps) to 70 hPa (Pt) adding the four available hours in the reanalyses and computing the daily average with the purpose of comparing the results with those of other authors.

[34] The mean field for **Q** (Figure 15a) shows a moisture flux that originates in the trade winds and turns eastward approximately north of 20°S. Another source of moisture, more evident at 40°W, is associated with the western sector of the South Atlantic Anticyclone. Both circulations converge in a zone with a northwest-southeast orientation coinciding with the mean position of the SACZ. The presence of a strong moisture flux over the central zone of the Del Plata basin is observed in Figure 15b which corresponds to the **Q** field for the CJEs. It is interesting to note the formation of a moisture convergence zone in the center-southeast portion of the SEAREA that is absent in the mean field with values higher than -20×10^{-5} kg m^{-2} s^{-1}. The anomaly of **Q** in Figure 15c shows a strong anomalous anticyclonic circulation centered on 28°S, 45°W associated both with an intensification of the low in the center of South America and a slight advance of the Atlantic subtropical anticyclone toward the continent. This anomaly is coherent with the weak SACZ circulation described by

Figure 15. (opposite) (a) Mean summer vertically integrated moisture flux in kg m^{-1} s^{-1}. Vertically integrated moisture flux convergence shaded every 10×10^{-5} kg m^{-2} s^{-1}. (b) As in Figure 15a but for CJEs. (c) As in Figure 15a but for vertically integrated moisture flux composite anomalies. Vertically integrated moisture flux convergence anomalies shaded every 3×10^{-5} kg m^{-2} s^{-1}.


a) Summer
b) Chaco Jet Events
c)
10N 5N EQ 5S 10S 15S 20S 25S 30S 35S 40S 45S 50S
80W 75W 70W 65W 60W 55W 50W 45W 40W 35W 30W
400
0
−10
−20
−30
0
−3
−6
−12
−15
−18

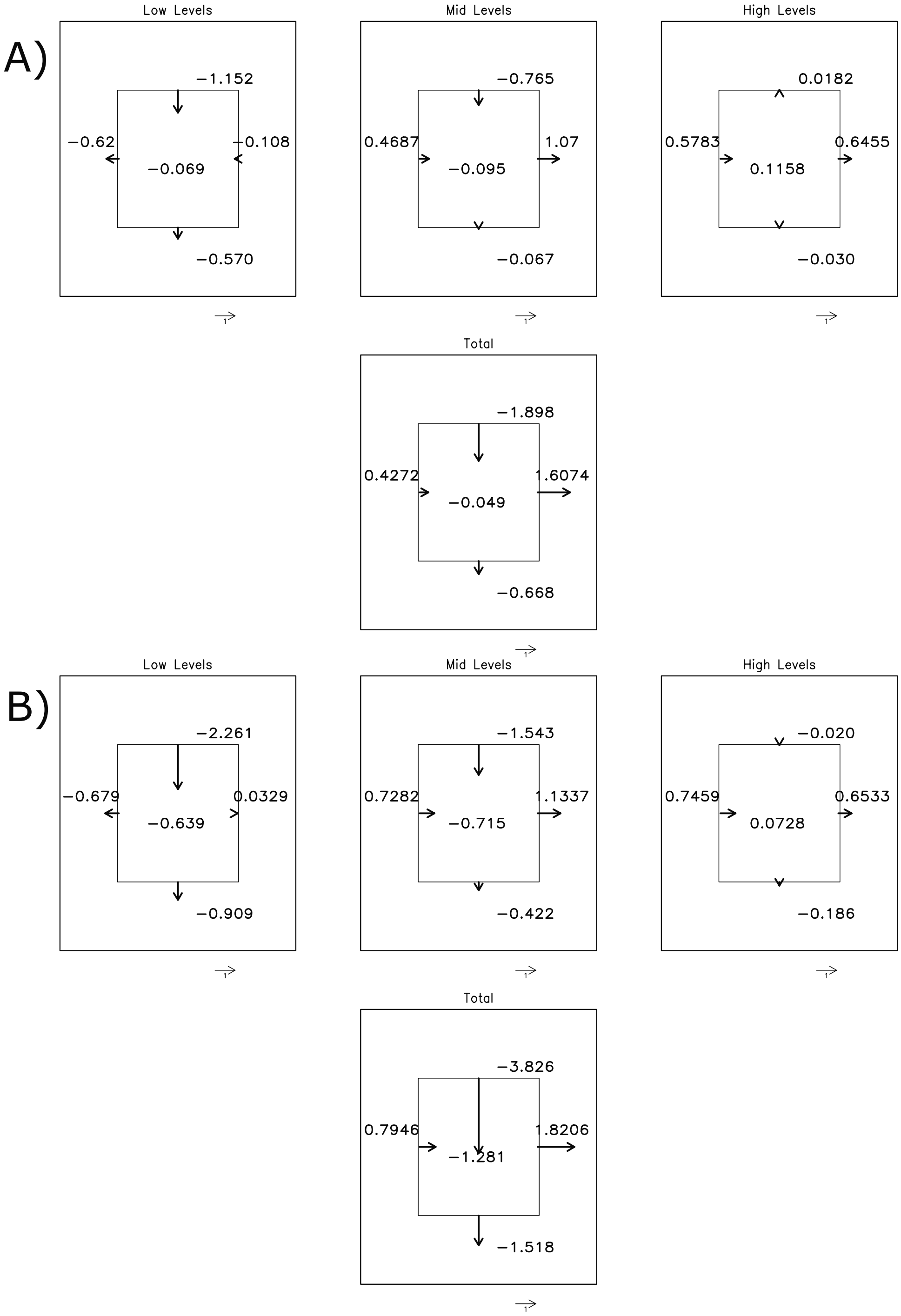


Figure 16. Net moisture flux divergence and net moisture flux in 10^8 kg s^{-1} over the region depicted by a rectangle in Figure 1 for (a) austral summer and (b) CJEs for low levels (Figures 16a and 16b left), mid levels (Figures 16a and 16b center), high levels (Figures 16a and 16b right) and all levels (Figures 16a and 16b bottom).

Nogués-Paegle and Mo [1997]. The equatorial zone shows no differences between the CJEs and the summer mean. In contrast, a strong moisture convergence anomaly consistent with the deceleration of **Q** is present over the SEAREA.

[35] The **Q** divergence in the SEAREA was calculated for the purpose of quantifying the moisture contributed by the CJE using the following equation:

$$\int_A \nabla \bullet \mathbf{Q} dA = \oint_L (\mathbf{Q} \bullet \mathbf{n}) dl, \qquad (2)$$

where L represents the curve that borders the A area

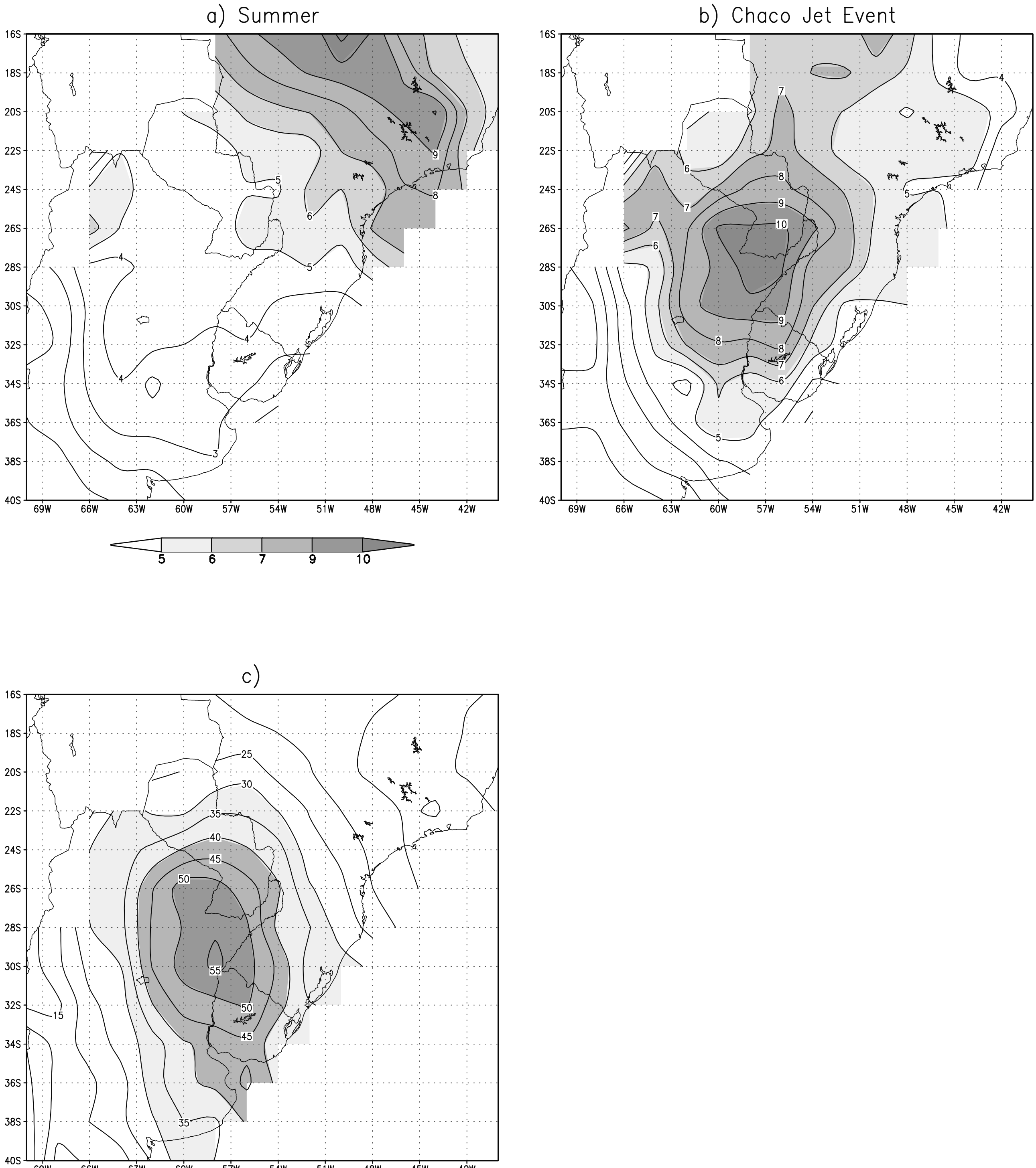


Figure 17. (a) Mean daily accumulated precipitation in mm d^{-1}. Contour interval is 1 mm d^{-1}, and values higher than 5 mm d^{-1}are shaded. (b) As in Figure 17a but for CJEs. (c) Contribution of the daily accumulated precipitation for CJEs relative to the respective value for the austral summer (in percent). Values higher than 40% are shaded.

(rectangle denoted in Figure 1) and **n** is a versor normal to the curve. The atmosphere was divided into three vertical layers: high (500, 400, 300, 250, 200, 150, and 100 hPa), middle (775, 700, and 600 hPa), and low (1000, 925, and 850 hPa), with the purpose of comparing the contribution of the different layers.

[36] Figures 16a and 16b show the respective results obtained from the evaluation of equation (2) for the selected box for both summer and the CJEs at the different layers. During the summer, there is a convergence of **Q** throughout the column, contributed by the low and mid layers, in which the northerly flux plays a dominant role. This convergence

is not evident in the global estimates obtained by *Peixoto and Oort* [1992], while *Wang and Paegle* [1996] find results similar to the present paper from ECMWF analyses in the 1989 austral summer for a region that contains the SEAREA. *Saulo et al.* [2000] also found similar results using operational ETA products for a region containing the zone under study during the spring and summer of 1997–1998.

[37] During the CJEs (Figure 16b), there is an important flux of humidity through the north face at middle and low levels, while at high levels this flux is negligible. During these episodes, convergence at low and mid levels is about 10 times more intense than the summer mean.

[38] Given the importance of this result for purposes of estimating the water balance in the Del Plata basin, it is important to enquire as to the impact of this convergence on another component of the water balance, such as the acumulated precipitation during these events.

[39] Figures 17a and 17b show the daily accumulated precipitation fields from an extensive rain gauge network corresponding to summer and to the CJEs, respectively. Figure 17c shows the relative contribution of the CJEs to the daily summer accumulated precipitation. Figure 17a depicts an important maximun located over SACZ area. Interesting to note is the displacement of the maximum toward the southwest during the CJEs, its position coinciding with the **Q** convergence maximum. Also, the maximum contribution to the accumulated precipitation attributable to the CJEs exceeds 55%. If it is recalled that the Chaco jet days amount to only 17% of the summer days, their contribution to the summer rainfall in this region is significant. In addition, the summer accumulated precipitation averaged over the SEAREA during CJEs is 6.1 mm d^{-1} that exceeds the mean seasonal value of 1.3 mm d^{-1}. This amount, which represents 35% of the total accumulated precipitation over the region, denotes the impact of these events on the SEAREA. The center of maximum activity of mesoscale convective complexes (MCCs) over South America, described by *Velasco and Fritsch* [1987], is located within the region displayed in the extreme precipitation composite of Chaco jet events. As these authors pointed out, large populations of MCCs occur in regions where low-level jets frequently develop. Recently, *Nicolini et al.* [2002] have characterized a sample of high precipitating mesoscale convective systems over southeastern South America during 1988–1993. They found that around 80% of these systems developed during CJEs. The mean position of their centers during mature stage is coincident with the maximum of relative contribution of the daily accumulated precipitation for CJEs. This coincidence is further evidence of a relationship between Chaco low-level jets environment and generation of intense organized convection; this is not addressed in the present paper.

6. Conclusions

[40] The Chaco Jet events selected for their particular southward extension in accordance with predetermined criterion represent a subensemble of low-level jet events east of the Andes that are infrequent in the ERA data set. Their duration varies from 1 to 10 days, although duration is more frequently from 1 to 5 days.

[41] The outstanding features of the circulation and the thermodynamic field that represent this ensemble are a maximum contrast of air masses in a latitude close to 39°S, the presence of a trough centered on 70°W within a baroclinic wave train penetrating from the Pacific Ocean, and a maximum of heat and moisture over the SEAREA.

[42] It is noticeable that using a completely independent manner of case selection as that adopted by *Nogués-Paegle and Mo* [1997] for the identification of SACZ, the large-scale circulation patterns associated with CJEs correspond fairly well to those of weak SACZ. This agreement suggests the strong signature of these phenomena over South American summer climate, which seems to alternatively be dominated by a SACZ-like or CJE-like regime. Nevertheless, further research is necesary in order to understand the mechanisms that favor one phase or the other, particularly in relation to their timescale.

[43] The OLR field during the CJEs used as a proxy for convection denotes a convectively unstable deep layer east of the Andes. This convection is associated with an extensive layer of strong low-level moisture flux convergence related to the deceleration of the jet and to the upper level wind divergence downwind of the trough. An intense maximum in the precipitation over the SEAREA is coherent with those fields.

[44] These strongly interdependent patterns between the precipitation and moisture convergence over the SEAREA during the CJEs, reinforce the hypothesis assumed by the selection criteria first designed by *Nicolini and Saulo* [2000], for the 15-year period between 1979 and 1993.

[45] Also, the intensity found in the water vapor flux anomaly at low and mid levels that characterizes these events reinforces the importance of studying them for the purpose of determining the water balance over the Del Plata basin.

[46] The statement that the CJEs represent an important characteristic of the SEAREA climate is founded on the fact that, although the CJEs only represent 17% of the austral summer days, they account for a significant fraction of the precipitation (a maximun of 55%) over northeastern Argentina. However, it is indispensable to contrast these results with future field experiments to test the hypothesis addressed in this paper.

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