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DIAGNOSTIC STUDY OF ENSO MODULATION OF THE LOW-LEVEL SOUTHWARD MOISTURE FLUX ACROSS CENTRAL SOUTH AMERICA DURING SUMMER AND ITS RELATED PRECIPITATION

Guillermo J. Berri[1,+] and Germán Bertossa
University of Buenos Aires, Argentina

1. INTRODUCTION

Precipitation variability in different timescales is tightly related to the atmospheric water vapor cycle functioning which, at the same time, depends on the variability of the atmospheric circulation on seasonal timescales. The El Niño-Southern Oscillation (ENSO) phenomenon is recognize as the most important driving mechanism of seasonal to interannual climate variability over vast tropical and subtropical regions of the planet, and central-southern South America is among those regions. Different authors have studied the influence of ENSO on the region's precipitation, for example Ropelewski and Halpert (1987, 1989), Pisciotano et al. (1994), and more recently Berri (2002a, 2002b) and Grimm (2003, 2004), among others. There is general agreement that the effects are more clearly seen around the peak of the ENSO event, i.e. between October of the year of onset and the following March. They also agree that El Niño is associated with positive precipitation anomalies and La Niña with negative precipitation anomalies over vast portions of central-southern South America. However, these signals present curious details about their timing within the summer semester, as well as their regional distribution, which will be discussed in the following sections.

On the other hand, the summer precipitation maxima in central and southern South America require large amounts of water vapor whose main source is in equatorial South America, brought into the continent by the easterly trade winds, from where it flows southward into Bolivia, Paraguay and central and northern Argentina. Therefore, the objective of this paper is to obtain a better understanding of the influence of El Niño and La Niña on the regional scale atmospheric circulation that modulate the low level southward moisture flux across central South America during summer. To this purpose, composites of El Niño and La Niña events during 1960-1998 are prepared, and the monthly anomalies of low level water vapor flux between October and March are analyzed.

2. DATA AND METHODOLOGY

The studied region, central South America –hereinafter CESA-, is to the east of the Andes Mountains and delimited between 40ºS-10ºS. According to the calculations of Labraga et al. 2000, the contribution of the upper levels is negligible, so we consider the vertically integrated water vapor flux vector between 1000 and 700 hPa, $\vec{Q}$, (for simplicity, it will be indistinctly referred to as low level water vapor flux, or simply water vapor flux), in the following way (Peixoto and Oort, 1992):

$$\vec{Q} = \left(g\rho_w\right)^{-1}\int_{1000}^{700} q\vec{V}dp \qquad \textbf{(1)}$$

where $\vec{V}$ is the horizontal wind vector, q is the specific humidity, g is the acceleration of gravity and ρ_w is the water density.

The wind components and specific humidity are taken at the following standard pressure levels: 1000, 925, 850 and 700 hPa. The monthly mean values of specific humidity, zonal and meridional winds components, geopotential height and pressure vertical velocity are obtained from the NCEP/NCAR reanalysis for the period 1960-1998. The monthly precipitation data are obtained from the UEA-CRU database (New et al.

[1] *Corresponding author address*: Department of Atmospheric and Oceanic Sciences, University of Buenos Aires, 1428 Buenos Aires, Argentina, e-mail: berri@at.fcen.uba.ar.
[+] Member of the National Research Council (CONICET) of Argentina

1999). All these data are available on a uniform 2.5º grid resolution.

The ENSO composites are obtained by averaging over the set of El Niño –EN- and La Niña –LN- years during the period 1960-1998. The criteria adopted to identify EN and LN years considers the following: a) five or more consecutive 3-month overlapped periods must have at least a +/-0.5°C, respectively, SST anomaly in the Niño3.4 region of the Pacific Ocean; and b) these periods must include OND, NDJ, DJF and JFM. The ENSO events generally begin during the first part of a calendar year, reach their peak by the end of that year and decay during the following year. Therefore, the adopted criterion guarantees that the conditions apply to the October-March study period. The considered events are periods of two consecutive years (see Table 1) that coincide with the list of warm (El Niño) and cold (La Niña) events of NOAA/CPC (www.cpc.noaa.gov).

Table 1 El Niño and La Niña events

El Niño years:	1963/64 - 1965/66 - 1968/69 - 1969/70 - 1972/73 - 1976/77 - 1977/78 - 1982/83 - 1986/87 - 1987/88 - 1991/92 - 1994/95 - 1997/98
La Niña years:	1964/65 - 1970/71 - 1973/74 - 1974/75 - 1975/76 - 1984/85 - 1988/89 – 1995/96 - 1998/99

3. DISCUSSION OF RESULTS

The following sections present, in first place, a brief description of the monthly October-March climatology of precipitation in CESA and low level water vapor flux over South America. This is followed by a comparative discussion of monthly EN and LN precipitation and water vapor flux anomalies, complemented with the analysis of the associated atmospheric circulation.

3.1 Monthly precipitation and water vapor flux climatology

Labraga et al. (2000) analyze the atmospheric water vapor cycle in South America and provide a discussion of the associated tropospheric circulation, so we refer the reader to that paper for further details about the participating physical mechanisms. For the sake of clarity we will only mention the key features of the atmospheric circulation that determine the summertime low level water vapor flux over CESA. During spring and summer, the water vapor influx into South America is dominated by the equatorial easterlies (figure not shown). The easterly trade winds that enter the continent attain a northeasterly component on the western side of the continent and create anomalous cross-equatorial water vapor flux. This is facilitated by the Andes Mountains that, acting as a barrier, force the low level flow to shift southward and southeastward, carrying moisture deep into the tropics and subtropics of South America. To the north of 40°S there is no water vapor entering the continent from the lower levels of the Pacific Ocean.

The key features in the upper levels are the anticyclonic circulation known as the Bolivian high (approximately at 15°S and 65°W), and a trough over northeastern Brazil. In the lower levels, the intensification of the low pressure system known as the Chaco low (approximately at 25°S and 60°W), in combination with the South Atlantic Ocean anticyclone, convey the water vapor from the Amazon basin towards central-eastern South America. This northwesterly moisture corridor, that crosses central South America and extends southeastward to the Atlantic Ocean, is present in every month from October to March at around 20ºS (figure not shown due to lack of space). The main driving mechanism of the moisture corridor is a wind maximum that develops in the lower levels over the region, known as the South American low level jet (SALLJ), which has been a subject of extensive research including a field experiment. We refer the reader to the article of Byerle and Paegle (2002), that provides and thorough review of the dynamics and the interannual variability of the SALLJ.

Maximum precipitation over CESA takes place in summer and its spatial distribution (figure not shown) shows the highest amounts over the Amazon basin in central Brazil. From that region, rainfall maxima project southeastward in the form of a band, known as the South Atlantic Convergence Zone (SACZ), characterized by high convective activity. SACZ is a dominant feature in summer basically sustained by the low level humid air convergence (Satyamurty et al. 1998).

3.2 El Niño and La Niña anomalies

Figure 1 shows water vapor flux anomalies (vectors) and precipitation anomalies (shading) from October to March of EN events. This period is characterized by positive precipitation anomalies over northern Argentina, most of Paraguay, Uruguay and the extreme south of Brazil, and a well-defined anomalous moisture influx into northern and central Argentina, more marked during November, December and March. In January there seems to be a bifurcation of the water vapor flux anomalies coming from the NW into northern CESA. As a result, moisture is directed eastward into central-eastern Brazil and southward into northern Argentina, the two places with positive precipitation anomalies. The period is characterized by the enhancement of the climatological water vapor flux (except in October), i.e. inflow over the northeastern part of the continent, counterclockwise shift with southeastward extension up to the midlatitudes of South America. The largest anomalies appear over the northwesterly moisture corridor in central South America. Over the eastern side of CESA, at tropical latitudes, the anomalies are very small and only important, in comparison to those at equatorial latitudes, during January (reduced influx) and February (enhanced influx). Over the northern part of the continent there is a reduced water vapor influx in every month except October.

Figure 2 shows water vapor flux anomalies (vectors) and precipitation anomalies (shading) from October to March of LN events. Except for January and February, the conditions over the southern half of CESA, and particularly the SE, are opposed to those observed during EN. The situation is now characterized by precipitation deficit and southerly water vapor flux anomalies (i.e. reduced northerly influx). Instead January, and to a lesser degree February, display similar positive precipitation anomalies to those observed during EN events. In particular, January presents the largest observed water vapor flux anomalies. Over southeastern CESA there is enhanced northwesterly moisture flux, in coincidence with large positive precipitation anomalies. In a regional context, the period is characterized by reduced moisture influx over northeastern South America, more marked from December to March. Thus, over northern South America the water vapor flux anomalies during EN and LN have an opposite behavior. Over the eastern side of CESA at tropical latitudes, there is reduced moisture influx, except in January when large moisture influx anomalies are seen around 10ºS-20ºS. This moisture influx combines with the enhanced northwesterly moisture corridor that crosses CESA to create an extended low level anticyclonic circulation anomaly, also seen during February and March although much weaker and confined over the continent.

The southeastern part of CESA, to the east of 65ºW and to the south of 25ºS, shows positive precipitation anomalies in every month from October to March during EN(see Fig. 1), while during LN the same region shows negative precipitation anomalies, with the only exception of January and, to a lesser degree, February (see Fig. 2). From NW to SE in CESA, across Bolivia, Paraguay, southern Brazil and up to the Atlantic Ocean, there is a water vapor transport corridor, as can be seen for example in Fig. 3 that shows the mean December condition. During December LN, the moisture corridor overlaps with the NW-SE band of positive precipitation anomalies, flanked to the north and to the south by extended regions with precipitation deficit, as seen in Figure 2c. The moisture corridor fuels and strengthens the South Atlantic Convergence Zone (SACZ), generating subsidence on both sides (see Fig. 4c), and reduced precipitation over central-eastern Brazil and northeastern Argentina. Nogués-Paegle and Mo (1997) found that intensification of the SACZ is associated with rainfall deficits over the subtropical plains (i.e. northeastern Argentina). The low level anticyclonic circulation anomaly over central-eastern Brazil (see Fig. 5a) concurs with the southwesterly water vapor flux anomalies over Argentina, increasing the moisture convergence over southern Brazil, where the only positive precipitation anomalies of the entire region are found. During January LN (Fig. 2d), positive precipitation anomalies appear over the region encompassed by northeastern Argentina, Uruguay and extreme southern Brazil, in contrast to the precipitation deficit seen in December (Fig. 2c) and March (Fig. 2f). Similar results were found in other studies, for example Pisciotano et al. (1994) over Uruguay, Grimm et al. (2004) in southern Brazil and Berri et al. (2002) in the upper Paraná River flows. In January the moisture corridor

(Fig. 6b) is stronger than in December (Fig. 6a), while in March (Fig. 6c) is much weaker, and there is a strong anticyclonic anomaly at 850 hPa over southeastern Brazil that extends into the Atlantic Ocean (Fig. 5b). The anticyclonic anomaly facilitates the moisture convergence into southern Brazil, Paraguay, Uruguay and northeastern Argentina, leading to the observed positive precipitation anomalies. Despite the strong southeasterly anomalous water vapor flux from the Atlantic Ocean into central-eastern Brazil, this region depicts negative precipitation anomalies. This is due to the subsidence over the area (see Fig. 4b) associated with the anticyclonic anomaly, so that the water vapor simply crosses the region to finally reinforce the NW-SE moisture vapor corridor.

It is interesting to analyze the situation in the upper levels and the changes that take place between December and January during EN as well as LN. In general, a clearly defined opposite pattern is found when comparing EN and LN events, and the latter one is characterized by larger anomalies. For example, over southeastern CESA there is a cyclonic anomaly in December of LN (the figures of the upper levels are not shown due to lack of space), in connection with downward motion in 500 hPa (see Fig. 4a) and precipitation deficit (see Fig. 2c). Instead, December of EN shows an opposite pattern with an anticyclonic anomaly (not shown), associated with upward motion in 500 hPa (Fig. 4c) and precipitation excess over the same region (Fig. 1c). In December of LN, over southern Brazil, there is an intensification of the subtropical jet (not shown), where upward motion (Fig. 4a) and positive precipitation anomalies prevail (Fig. 2c). However, such intensification of the subtropical jet is not found during EN when the anomalies are much smaller (not shown), so the subtropical jet prevails in its mean condition.

During January of EN, the 200 hPa positive westerly wind anomalies (not shown) adopt a wavelike pattern that reinforce the subtropical jet over the region where positive precipitation anomalies are found (Fig. 1d). During LN the easterly wind anomaly, associated with the anticyclonic anomaly around 40ºS over the Atlantic Ocean, contributes to weakening the subtropical jet (not shown).

4. SUMMARY AND CONCLUSIONS

The ENSO modulation during the summer semester – October through March- of the low-level southward moisture flux across central South America (40ºS-10ºS) – CESA- is studied by means of El Niño and La Niña composites of the NCEP/NCAR reanalysis and EUA_CRU precipitation database during 1960-1998. The period October-March of EN events is characterized by positive precipitation anomalies over northern Argentina, most of Paraguay, Uruguay and southernmost Brazil, and a well-defined anomalous moisture influx into northern and central Argentina, more marked during November, December and March. In January there seems to be a bifurcation of the water vapor flux anomalies coming from the NW into northern CESA, which directs moisture towards the east, into central-eastern Brazil, and to the south into northern Argentina, two places that show positive precipitation anomalies. On the regional scale, the period is characterized by the enhancement of the climatological water vapor flux (except in October), i.e. inflow over the northeastern part of the continent, counterclockwise shift and southeastward extension up to the midlatitudes of South America. The largest anomalies appear over a NW-SE moisture corridor across CESA. Over the eastern side of the continent, at tropical latitudes, the anomalies are very small and only important, in comparison to those at equatorial latitudes, during January (reduced influx) and February and March (enhanced influx). Over the northern part of the continent there is a reduced water vapor influx in every month except October. During the same period of LN events, every month shows reduced northeasterly moisture influx into the continent, particularly from December. The conditions over the southern half of CESA are, in general, opposed to those observed during EN, i.e. precipitation deficit, with the exception of January, and to a lesser degree February, that display positive precipitation anomalies similar to those observed during EN events. In particular, January presents the largest observed water vapor flux anomalies.

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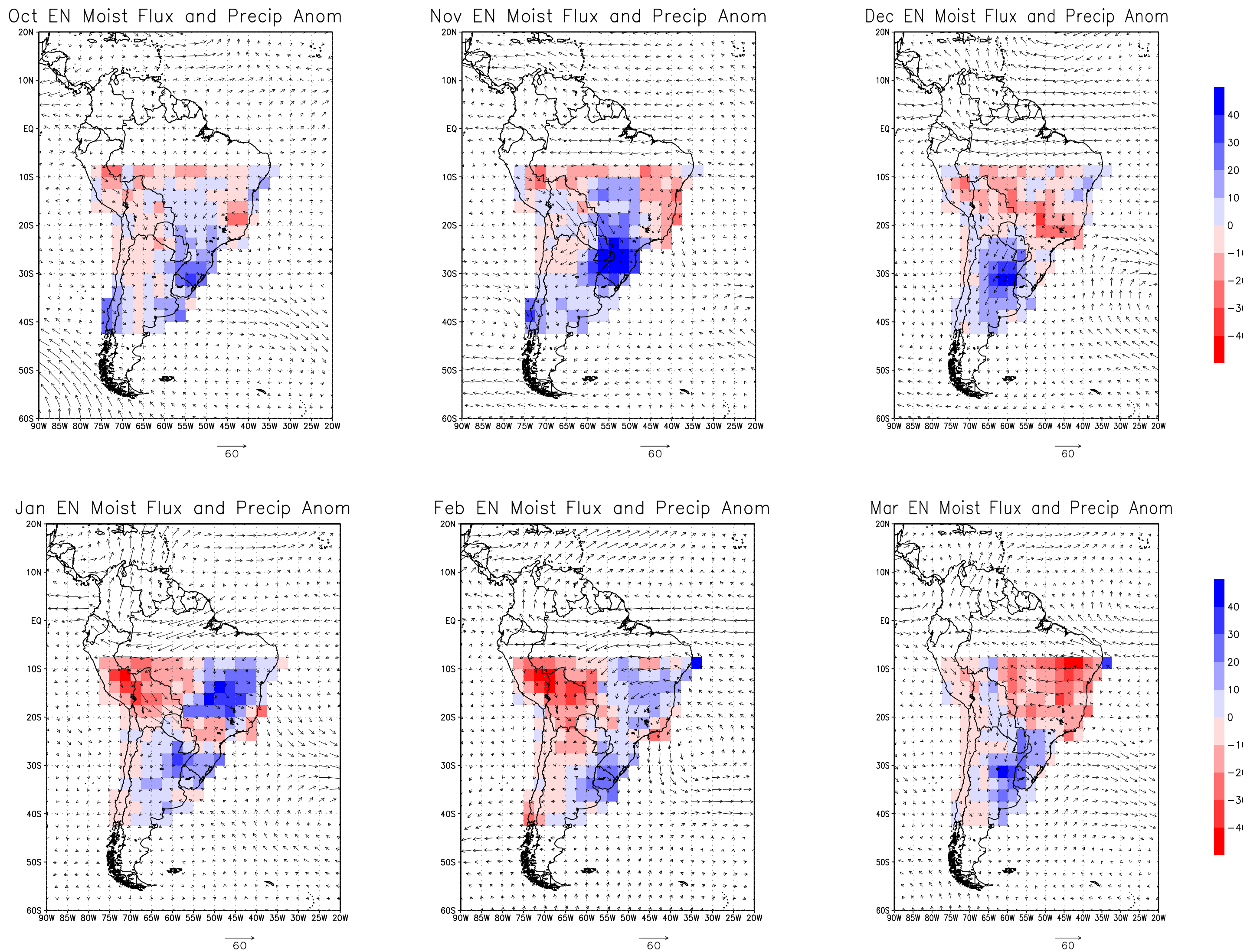

Figure 1 El Niño composite anomaly of vertically integrated 1000/700 hPa horizontal water vapor flux (vectors) and precipitation (shading) corresponding to a) to f) October to March (clockwise from upper-left corner, respectively). The period is 1960-1998. The arrow scale represents 60 mm m s^{-1} and the shading scale is in mm.

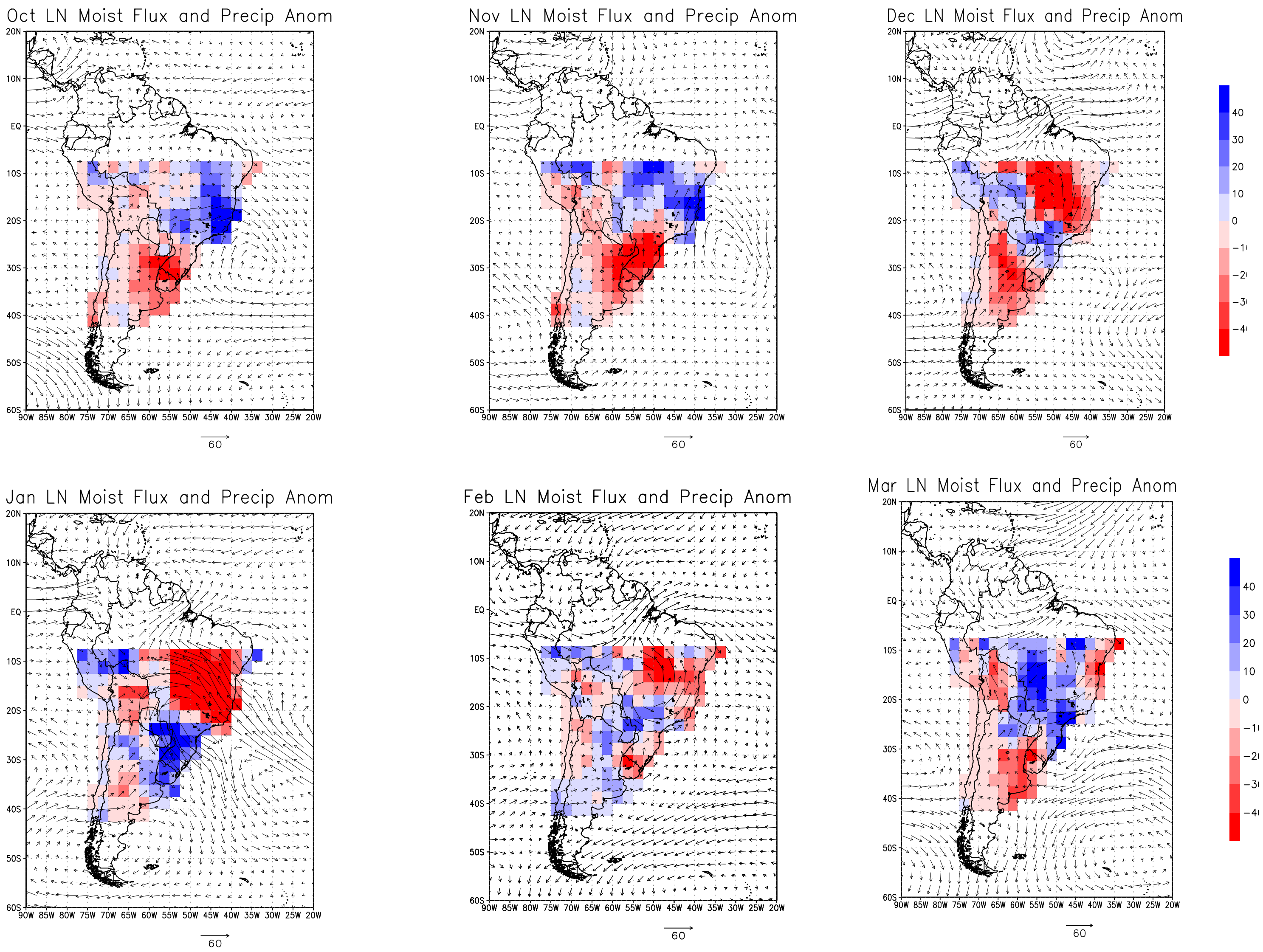

Figure 2 Same as Figure 1, but for the La Niña composite anomaly.

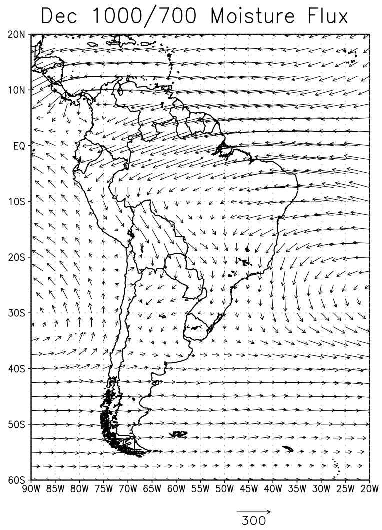

Figure 3 Mean vertically integrated 1000/700 hPa horizontal water vapor flux corresponding to December 1960-1998. The arrow scale represents 300 mm m s^{-1}

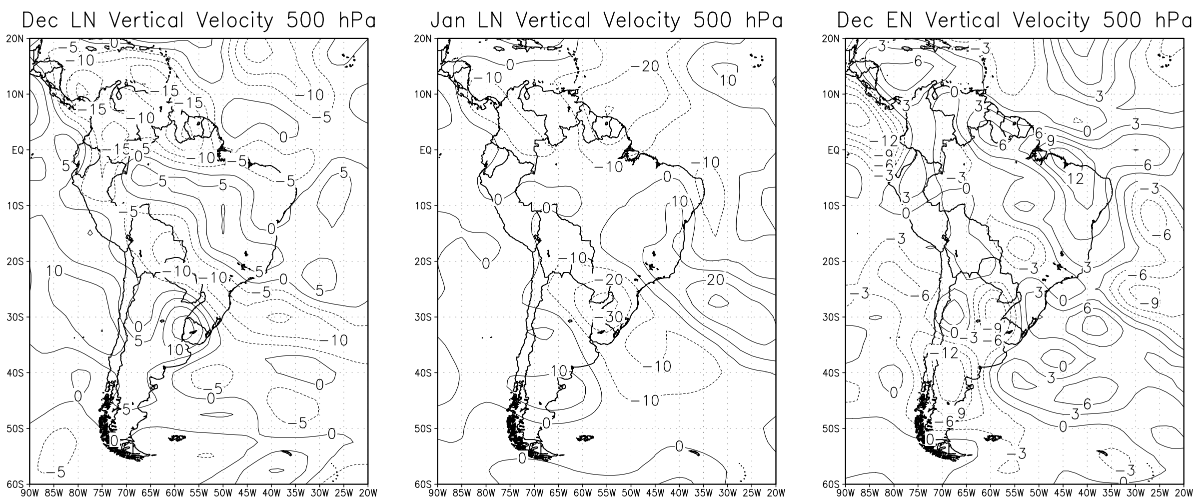

Figure 4 Composite anomaly of pressure vertical velocity at 500 hPa corresponding to a) December La Niña (left), b) January La Niña (center) and c) December El Niño (right). The period is 1960-1998. Contours are in 10^2 Pa s^{-1}

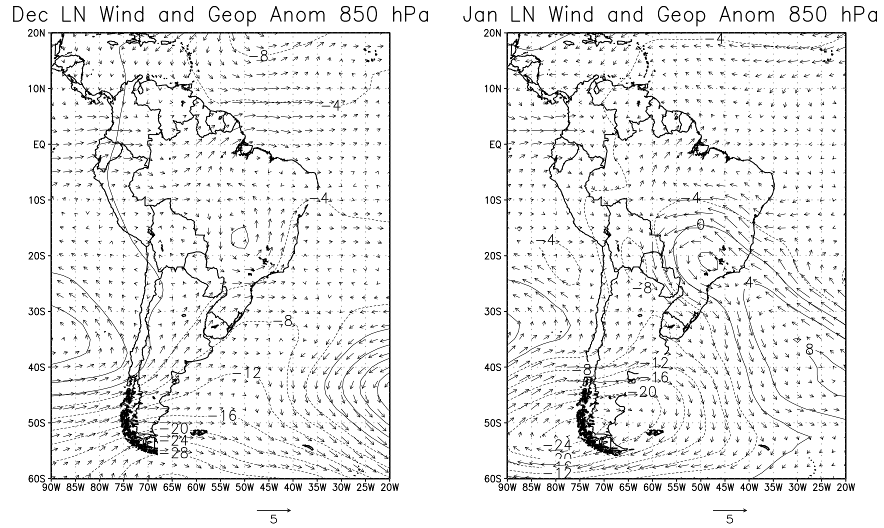

Figure 5 Composite anomaly of 850 hPa wind (vectors) and geopotential (contours) corresponding to a) December La Niña (left) and b) January La Niña (right). The period is 1960-1998. The arrow scale represents 5 m s^{-1} and contours are in m.

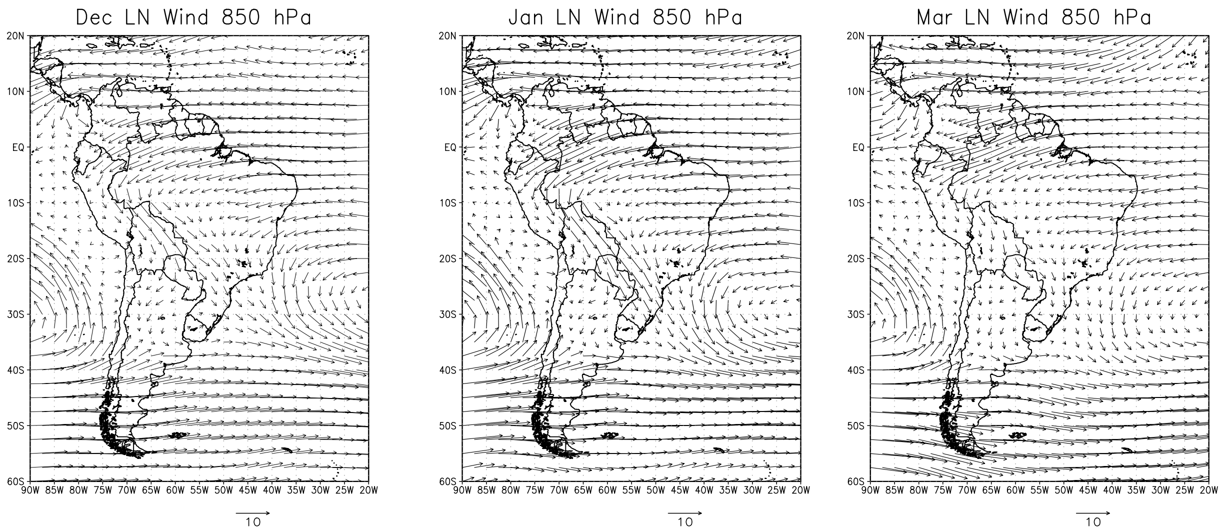

Figure 6 Mean 850 hPa wind composite corresponding to a) December La Niña (left), b) January La Niña (center) and c) March La Niña (right). The period is 1960-1998. The arrow scale represents 10 m s^{-1}.