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ENSO impacts on the South American rainfall during 1980s: Hadley and Walker circulation

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RESUMEN

Los cambios en las células de Hadley y Walker y sus respectivos impactos en Suramérica, en las lluvias, durante los episodios en ENOS, observados en la década de los 80, son investigados a través de análisis de reacciones cruzadas de la circulación atmosférica en altitudes promediadas en planos zonal y meridional. Tales células de gran-escala, casi invirtieron su patrón de circulación climatológica durante los eventos de El Niño (1982-83 y 1986-87). En esos años, manifestación de ramas de descenso anómalo de las células de Hadley y Walkers afectaron la mayor parte del norte-noreste de Suramérica, con inhibición de actividad convectiva asociada a ITCZ y causó condiciones de sequía en la estación lluviosa de Guyana, Surinam, Guyana Francesa, centro-este del Amazonas y la mayor parte del noreste de Brasil. Por otra parte las condiciones de exceso de precipitación observada en el sur-sureste de Suramérica, fueron favorecidas por la rama de ascenso anómalo de las células de Hadley. Durante los eventos de la niña (1984-85 y 1988-89), se observó una intensificación del ascenso y descenso de las ramas asociadas a las células de Hadley y Walker. El movimiento anómalo de gran-escala ascendente asociado a las células, fue extendido al noreste del Brasil y sur de Atlántico ecuatorial, favoreciendo que ITCZ se vuelva más activo que el normal, con resultados en un aumento del común en la estación lluviosa en esas áreas. Una intensa subsidencia fue notada en las latitudes medias de Suramérica, la cual inhibió la convección en gran-escala en la región, explicando la deficiente estación lluviosa observada en la mayor parte del sur-sureste de Suramérica.

ABSTRACT

The changes in the Hadley and Walker cells and their respective impacts on the South American rainfall during the ENSO episodes observed in the decade of 80, were investigated through cross-sections analyses of the atmospheric circulation in altitude, averaged in the zonal and meridional planes. Such large-scale cells almost inverted their climatological circulation pattern, during El Niño events (1982-83 and 1986-87). In these years, manifestation of the anomalous descending branch of the Hadley and Walker cells affects most of the north-northeast of South America, which inhibited the convective activity associated to ITCZ and caused drought conditions in the rainy seasons of the Guyana, Surinam, French Guiana, center-east of the Amazon and most of the Northeast Brazil. On the other hand, conditions of excess of precipitation observed in the south-southeast of South America, were favored by the anomalous ascending branch of the Hadley cell. During La Niña events (1984-85 and 1988-89), it was observed an intensification of the ascending and descending branches associated to the Walker and Hadley cells. The anomalous large-scale ascending movement associated to these cells, was extended to the Northeast of Brazil and equatorial South Atlantic, favoring ITCZ to become more active than the normal, which resulted in an above normal rainy season in these areas. An intense subsidence was noticed in the mid latitudes of South America, which inhibited the large-scale convection in the region, explaining the deficient rainy season observed in most of the south-southeast of South America.

Key words: Hadley circulation, Walker circulation, ENSO, South American Rainfall.

1. Introduction

Most of the annual total rainfall observed over the South America usually occurs during the austral summer (December to February - DJF) and autumn (March to May - MAM) months. In the Figure 1, that shows the seasonal percentages of the annual total precipitation to the DJF and MAM periods, it is clearly observed that the months of DJF are the rainiest in most of the South American continent. The large and synoptic meteorological systems that modulate the rainfall in this period are linked to the performance of the South Atlantic Convergence Zone - SACZ (Casarin and Kousky, 1986; Figueroa *et al.*, 1995; Nogués-Paegle and Mo, 1997), Bolivian High and the upper tropospheric cyclonic vortices (Virji, 1981; Kousky and Gan, 1981; Kayano *et al.*, 1997). In the subsequent period, MAM, the rainy season is located on the center-east of the Amazon and Northeast of Brazil, which is modulated by the migration to the south of Equator of the Inter Tropical Convergence Zone - ITCZ (Hastenrath and Heller, 1977; Moura and Shukla, 1981; Nobre and Shukla, 1996, Souza *et al.*, 1998b).

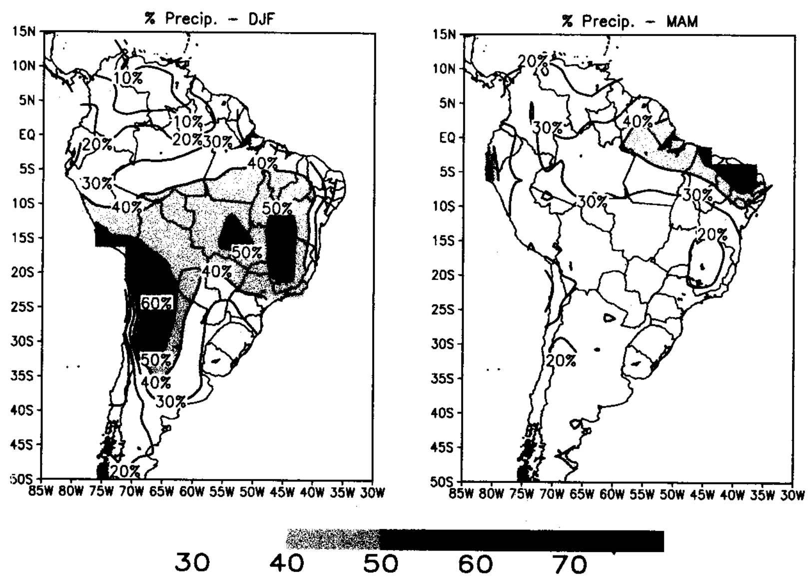

Fig. 1. Seasonal precipitation percentage (in relation to the total annual) over South America for the DJF and MAM periods. The long-term mean refers to the period from 1961 to 1990. The contour interval is 10% and the values above 30% are shaded.

The so-called El Niño-Southern Oscillation - ENSO, is considered one of the most prominent sources of interannual variations in weather and climate around of the world (Trenberth and Caron, 2000). ENSO, a phenomenon of planetary scale related to a strong and complex ocean-atmosphere coupling over the tropical Pacific basin (Cane, 1992), has a cycle, with the El Niño (warm phase) manifesting in one extreme phase and the La Niña (cold phase) in the opposite extreme. The major atmospheric and oceanic features associated with El Niño episodes are: predominance of positive anomalies of sea surface temperature (SST), weakness of the trade winds in the surface and low pressure with deep convection on the oriental Pacific and high pressure with subsidente movement on the western Pacific, Indonesia and Australia. La Niña events feature reversed atmospheric and oceanic patterns (Kousky and Ropelewski, 1989). These anomalous patterns occur over the tropical Pacific basin, including an extensive spatial area of the tropics (more than a third of the tropical belt around of the globe). Hence, ENSO deflagrates changes in the general circulation of the atmosphere, resulting in climatic impacts in several continental areas located in the tropics and extratropics. These changes are basically related to the weakness, intensification and/or displacements of the large-scale atmospheric circulation in the meridional and zonal planes, mainly those linked to the Hadley and Walker circulations (Kidson, 1975; Kousky *et al.*, 1984). The Walker circulation is a result of the "see-saw" in surface pressures between the eastern and western hemispheres linking these action centers through an atmospheric circulation in the zonal direction, restricted to the tropics, with ascending branch over the western Pacific and descending branch over the eastern Pacific (Bjerknes, 1969). On the other hand, the differential heating between tropic-extratropics, results in the formation of a meridional circulation, the Hadley Circulation, with ascending branch over the equatorial areas and descending branch over the subtropical latitudes (around 30° of latitude) in both South and North Hemispheres (Hastenrath, 1985).

South America is one of the continental areas around the world that is directly influenced by the ENSO cycle (Ropelewski and Halpert, 1987). Several studies documented the ENSO impacts (mainly the El Niño events) in the South American rainfall (e.g., Aceituno, 1988; Rao and Hada, 1990; Alves and Repelli, 1992; Grimm *et al.*, 1998; Uvo *et al.*, 1998; Diaz *et al.*, 1998; Coelho *et al.*, 1999). These studies indicate, in general, that the main areas of South America influenced by ENSO are located at the sections west (Peru and Ecuador), north and northeast (Amazon and Brazilian Northeast) and south-southeast (South of Brazil, Uruguay and Argentina).

This work provides a comprehensive diagnostic analysis of the changes in the large-scale atmospheric circulation, related with the Hadley and Walker cells, during the phases of ENSO (El Niño and La Niña events) observed in the decade of 80. This decade was marked by strong interannual climatic variations, particularly, over South America, forced by the occurrences of the El Niño events observed in 1982-83 and 1986-87 and by the La Niña events of 1984-85 and 1988-89. It is interesting to note that there was almost two years period between the extreme events studied here. In these analyses, emphasis is given to the changes observed in the Hadley and Walker cells, particularly for the South America sector, verifying the respective impacts in the precipitation observed during summer and autumn seasons.

2. Data and methodology

The monthly data set for the decade of 80 consists of zonal, meridional and vertical wind components and specific humidity in the levels of 1000, 925, 850, 700, 600, 500, 400, 300, 250 and 200 hPa, as well as their respective long-term mean, obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research - NCEP/NCAR reanalysis project (Kalnay *et al.*, 1996). These data are disposed in a global grid with spatial resolution of 2.5 degrees in latitude and longitude. In addition, it was used the monthly data of precipitation observed over South America, gained from the NCEP global archives (ftp://ncep.noaa.gov/precip) with horizontal resolution of 2.5 degrees in latitude and longitude. These data were generated using a vast group of derived information of monthly observations of precipitation, estimates of satellites and results of numeric models (Xie and Arkin, 1996). The global SST data, with spatial resolution of 1 degree of latitude and longitude, were extracted from last version of Comprehensive Ocean-Atmosphere Data Set - COADS, compiled by Da Silva *et al.* (1994).

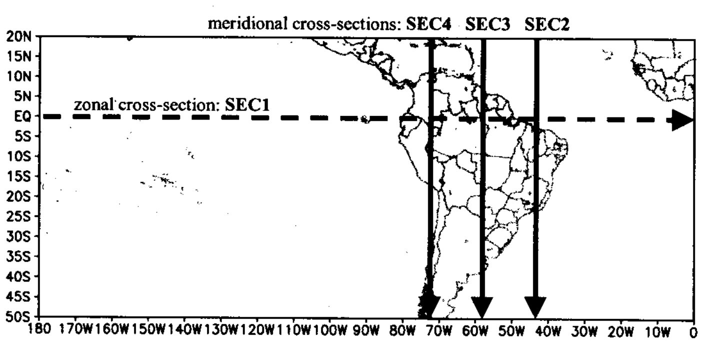

Fig. 2. Spatial domain of the area in study. The arrows represent the areas where the vertical cross-sections were calculated. SEC 1 represents the zonal cross-section (longitude x height), averaged in the equatorial latitudinal band of 5°S-5°N. SEC 2, SEC 3, and SEC 4 represent the meridional cross-sections (latitude x height), averaged in the longitudinal bands of 50°W-35°W, 65°W-50°W and 80°W-65°W, respectively.

The large-scale atmospheric circulation patterns related with the Hadley and Walker cells were investigated, with emphasis to the Pacific, South America and Atlantic domain (Fig. 2), through the plotting and analyses of the vertical cross-sections of the upper atmospheric circulation (zonal, meridional and vertical components of the wind vector) and specific humidity from 1000 up to 200 hPa levels during DJF and MAM seasons. Therefore, for the analyses of the Walker circulation, vertical cross-sections were plotted in the zonal direction (longitude x height), averaged along the equatorial area (5S-5N), over the regions located between the tropical Pacific, South America and tropical Atlantic, as shown the SEC1 in the Figure 2. Similarly, for the analyses of the Hadley circulation, vertical cross-sections were plotted in latitude, averaged in three longitudinal bands (SEC2, SEC3 and SEC4) along South America (Fig. 2).

3. Results

Figure 3 shows the vertical structure in longitude of the seasonal climatological pattern of the specific humidity and east-west wind vector field (zonal and vertical components), representing part of the Walker circulation over the tropical belt comprising the Pacific, South America and Atlantic sector. During DJF and MAM periods, the ascending branch of the Walker cell acts over western Pacific and the consequent descending branch is located in the eastern Pacific area, close to the west coast of South America (120W to 95W, approximately). Over the equatorial portion of South America (including Ecuador, north of Peru, center-south of Colombia, Venezuela, and great part of the Brazilian Amazon) there is strong ascent motion and a compensatory subsidence reaching the center-east of Atlantic Ocean. In the areas of ascending movement of the air, it is noticed the presence of excess of the specific humidity from the surface to the medium levels of the troposphere, while in the descending areas the amount of humidity decreases considerably.

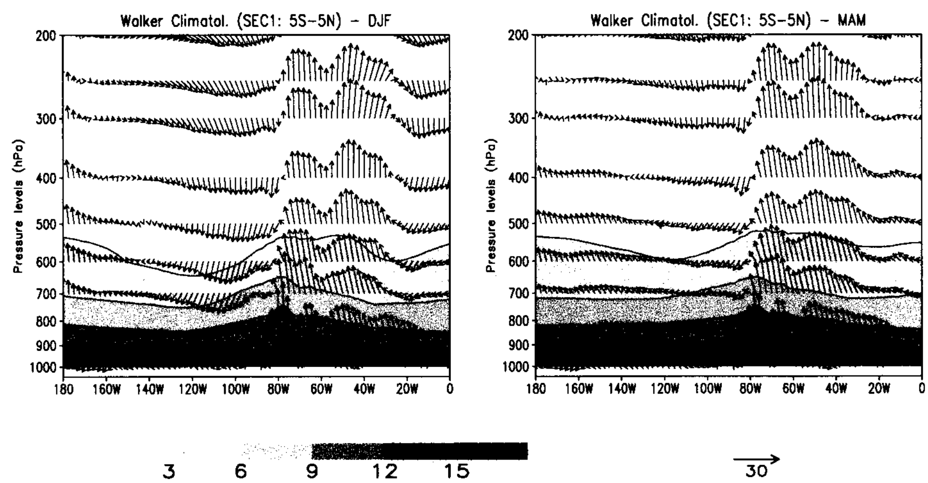

Fig. 3. Zonal vertical cross-sections (longitude x height) of the seasonal climatological pattern of the specific humidity (shaded contours in units of g/Kg) and east-west wind vector field (arrows in units of Pa m/s), averaged between 5°S-5°N (SEC 1), for the DJF and MAM periods. The long-term mean refers to the period from 1979 to 1994.

Figure 4 shows the vertical structure in latitude of the seasonal climatological pattern of the specific humidity and north-south wind vector field (meridional and vertical components), representing part of the Hadley circulation, particularly, over the longitudinal bands that include the South America area (see Fig. 2). In these fields and both periods it is observed the atmospheric circulation pattern associated to the Hadley cell, showing ascending branch and excess of humidity over the tropical latitudes of South America (from Equator to 20°/25°S, approximately), while the descending branch reaches the subtropical latitudes (between 30° and 35°S), where the presence of atmospheric humidity is low. In the cross-section averaged from 80°W to 65°W (Fig. 4, SEC4), it is observed the presence of the Bolivian high close to its climatological position (15°S to 25°S, approximately), during the DJF period. In the next period, MAM, the ascent branch of the Hadley circulation is narrower and weaker, the Bolivian High is less marked and the amplitude of the subsidence over the tropics seems to be smaller. In fact, these features just emphasize that the autumn season represents the transition between summer and winter.

In the following sections, several vertical cross-sections of the atmospheric circulation associated to the Hadley and Walker cells are analyzed. These cross-sections will show field anomalies, which is defined as the seasonal values minus the respective long-term mean.

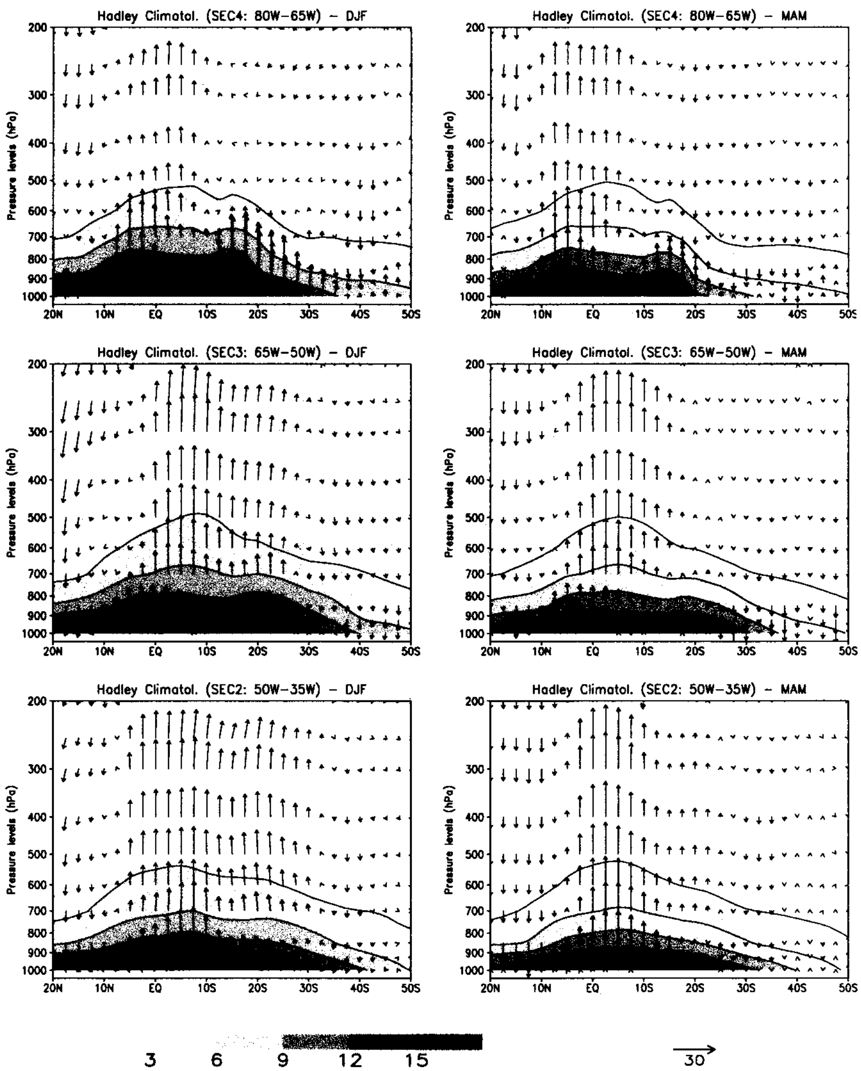

Fig. 4. Meridional vertical cross-sections (latitude x height) of the seasonal climatological pattern of the specific humidity (shaded contours in units of g/Kg) and north-south wind vector field (arrows in units of Pa m/s), averaged between the longitudinal bands of 50°W-35°W (SEC 2), 65°W-50°W (SEC 3) and 80°W-65°W (SEC 4), during DJF (left figures) and MAM (right figures). The long-term mean refers to the period from 1979 to 1994.

a. Walker Cell during El Niño and La Niña

The sequence in Figures 5 and 6 show the vertical structure of the specific humidity anomalies and the zonal (east-west) wind vector anomalies (zonal and vertical wind components) averaged between 5°S-5°N (top panel); SST anomalies observed over Pacific and Atlantic Oceans (intermediate panel); and percentages deviations of precipitation observed over South America (lower panel), during DJF and MAM, respectively, for the El Niño events observed in 1982-83 (left figures) and in 1986-87 (right figures). From these figures, it is clear that the general patterns are similar in both El Niño events, however there are also some regions presenting different features. The SST positive anomalies over the tropical Pacific induce the formation of deep convection, positive anomalies of specific humidity and also strong anomalous ascent motion in most of the troposphere along the Pacific and west coast of South America region (between 180° and 85°W). This ascending movement in the western South America favored the occurrence of positive deviations of precipitation in Ecuador and north of Peru during the DJF and MAM periods. Simultaneously, in the tropospheric layer located in the equatorial areas of South America (where usually there is ascent movement), we mostly see sinking movement anomalies, indicating a significant weakness of the vertical movement over the Amazonian region. These descending atmospheric anomalies extend from the Amazon to the Brazilian Northeast and east equatorial Atlantic, partially explaining the below normal rainy season in the north and northeast sectors of South America.

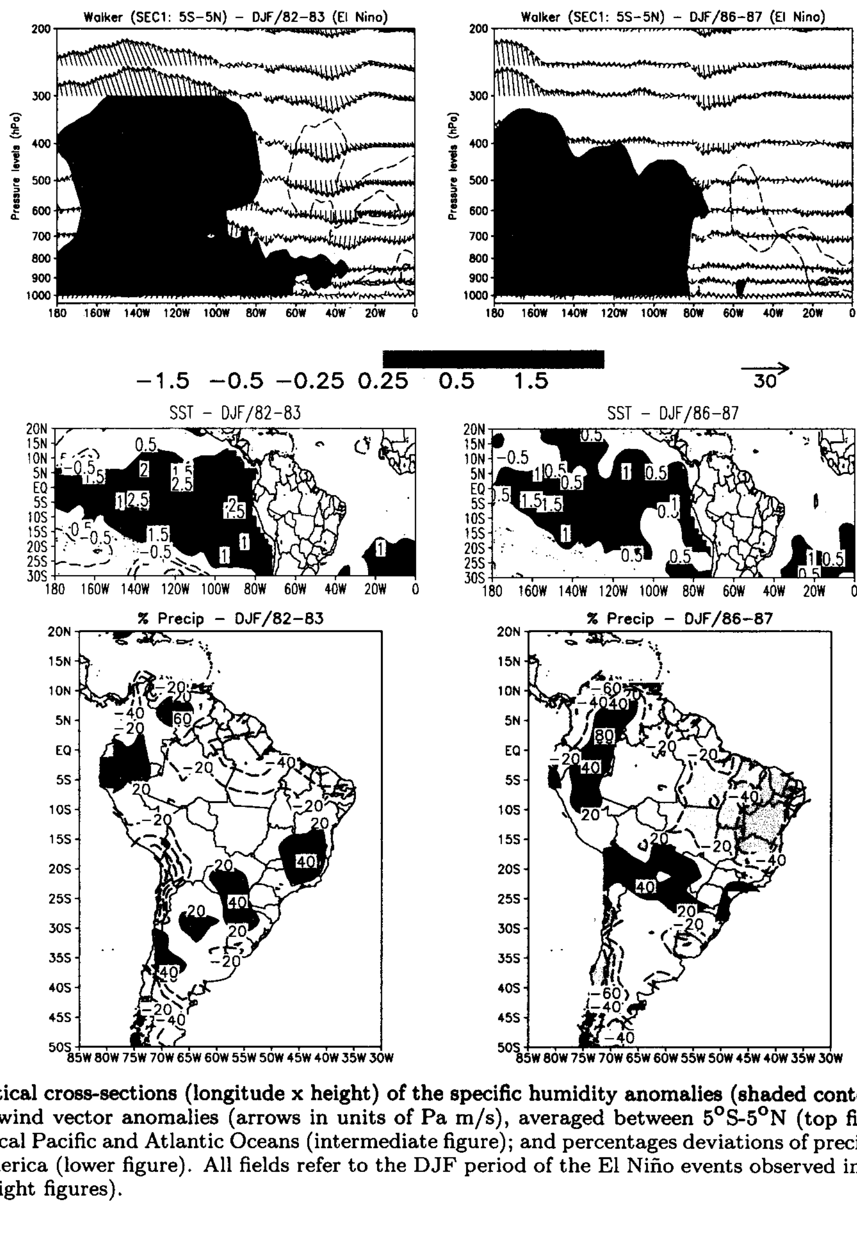

Fig. 5. **Zonal vertical cross-sections (longitude x height) of the specific humidity anomalies (shaded contours in** units of g/Kg) and east-west wind vector anomalies (arrows in units of Pa m/s), averaged between 5°S-5°N (top figure); SST anomalies (°C) over tropical Pacific and Atlantic Oceans (intermediate figure); and percentages deviations of precipitation (%) observed over South America (lower figure). All fields refer to the DJF period of the El Niño events observed in 1982-83 (left figures) and 1986-87 (right figures).

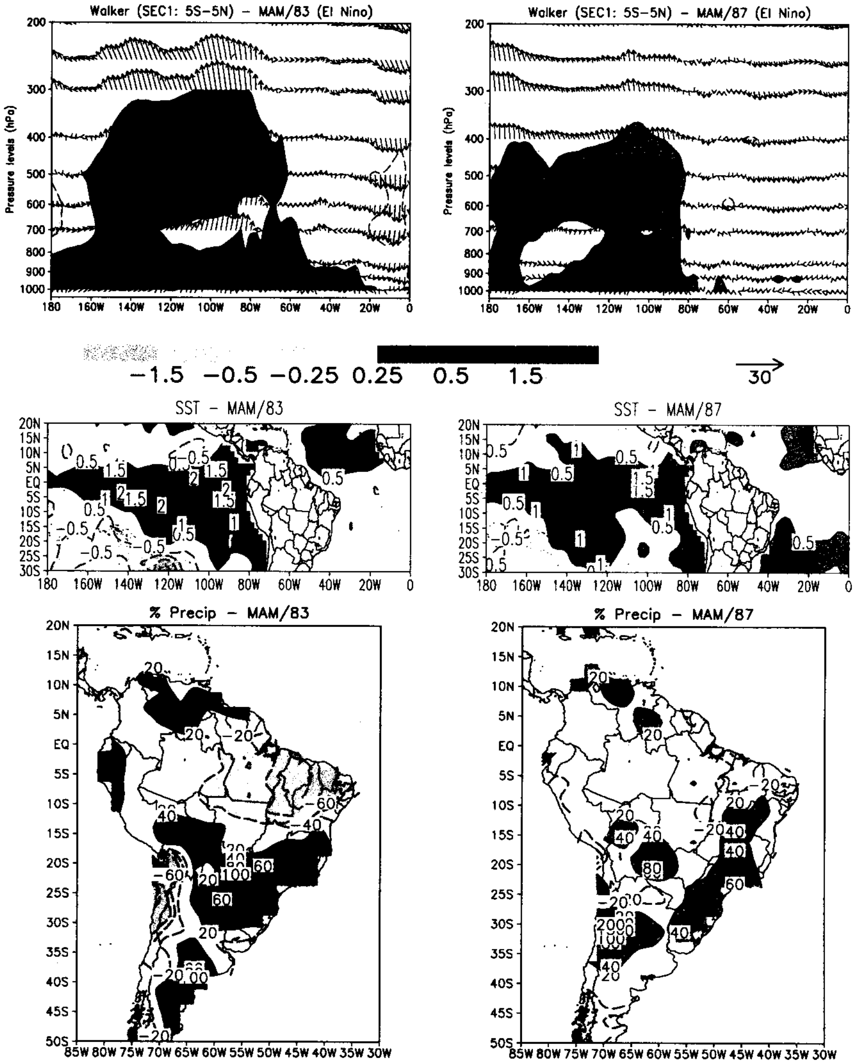

Fig. 6. As in Figure 5 but for the MAM period of the El Niño events observed in 1982-83 (left figures) and 1986-87 (right figures).

It is also interesting to observe that though the amplitude of the SST during the El Niño of 82/83 was higher than 86/87, the percentages of precipitation deviation in the north and northeast of South America was bigger during the DJF period of the 86/87 event (Fig. 5). However, this feature is completely different in the MAM period (Fig. 6), where during the first Niño, there is over 100% of positive precipitation deviation in the center-south part of South America (i.e., in the Paraguay, northern Argentina and south of Brazil) and negative deviation in the north and northeast part of Brazil. It can be seen from the Walker circulation that there is a strong ascent anomaly near the equatorial west coast of South America and subsidence over the north region of the continent. This pattern explains the differences observed on the precipitation deviation between these two negative ENSO events. The pattern observed at the mid latitude will be explained by the anomaly in the Hadley circulation discussed in the next section.

The same analyses described above were used for the La Niña episodes observed during 1984-85 and 1988-89 years (Figs. 7 and 8). The atmospheric patterns associated to La Niña years are essentially configured as opposite to the El Niño characteristics. In the tropical Pacific and west coast of South America (between 180° and 80°W), where the negative SST anomalies dominate, we observe negative anomalies of specific humidity and an intense anomalous descending movement from the surface up to 200 hPa. The predominance of the descending air causes the inhibition of the large-scale convection and it is usually associated with drier rainy seasons in the western South America (Ecuador and Peru). On the other hand, in the north and northeast areas of the South American continent, we observe positive anomalies of humidity and ascent movement anomalies, indicating an enhancement of the ascending branch of the Walker cell in these regions. Therefore, the Guyana, the Amazon and the Brazilian Northeast regions exhibit significant positive deviations of precipitation in the periods of DJF and MAM. We should also note that the southern part of Brazil, Paraguay and northern Argentina show different precipitation deviation from one even La Niña to the other. In particular, during the MAM period of 85 (Fig. 8), we see positive deviation when compared to 89. Coelho *et al.* (1999) have found similar results in their composites of weak and strong ENSO events. It seems that dry condition is the dominant feature over this region when the La Niña event is strong, as it was in 89.

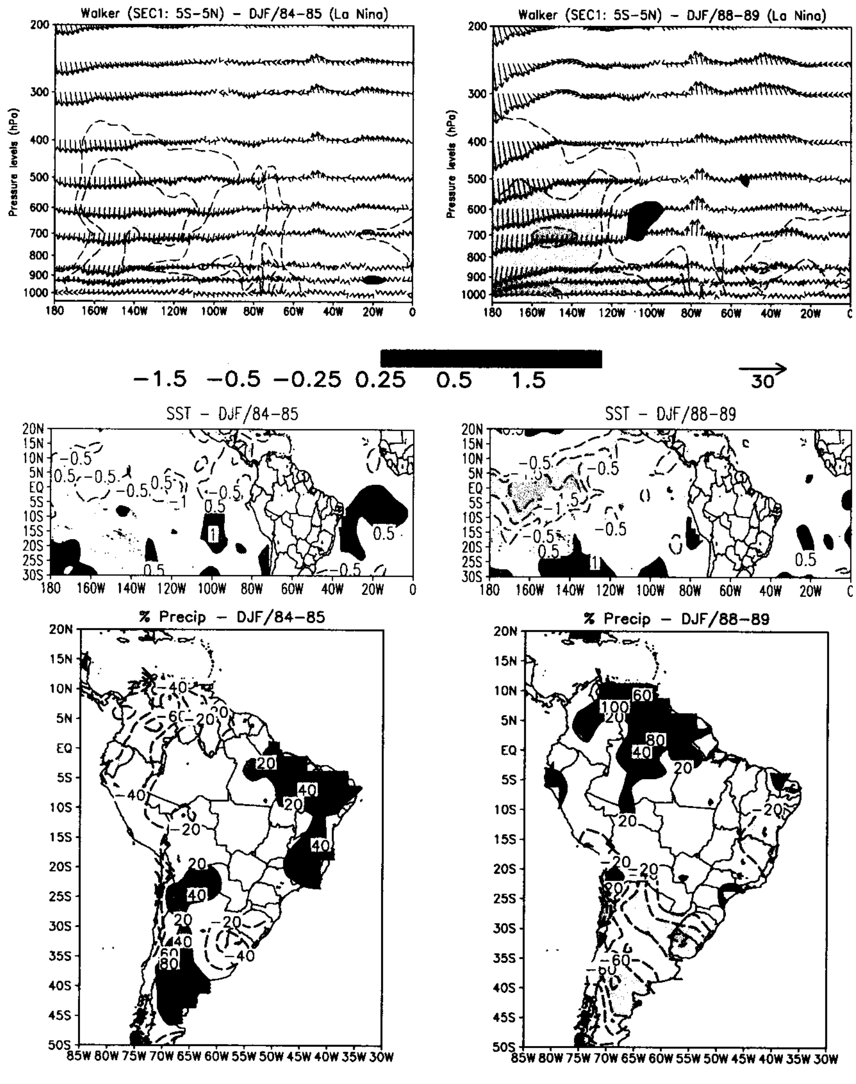

Fig. 7. As in Figure 5 but for the DJF period of the La Niña events observed in 1984-85 (left figures) and 1988-89 (right figures).

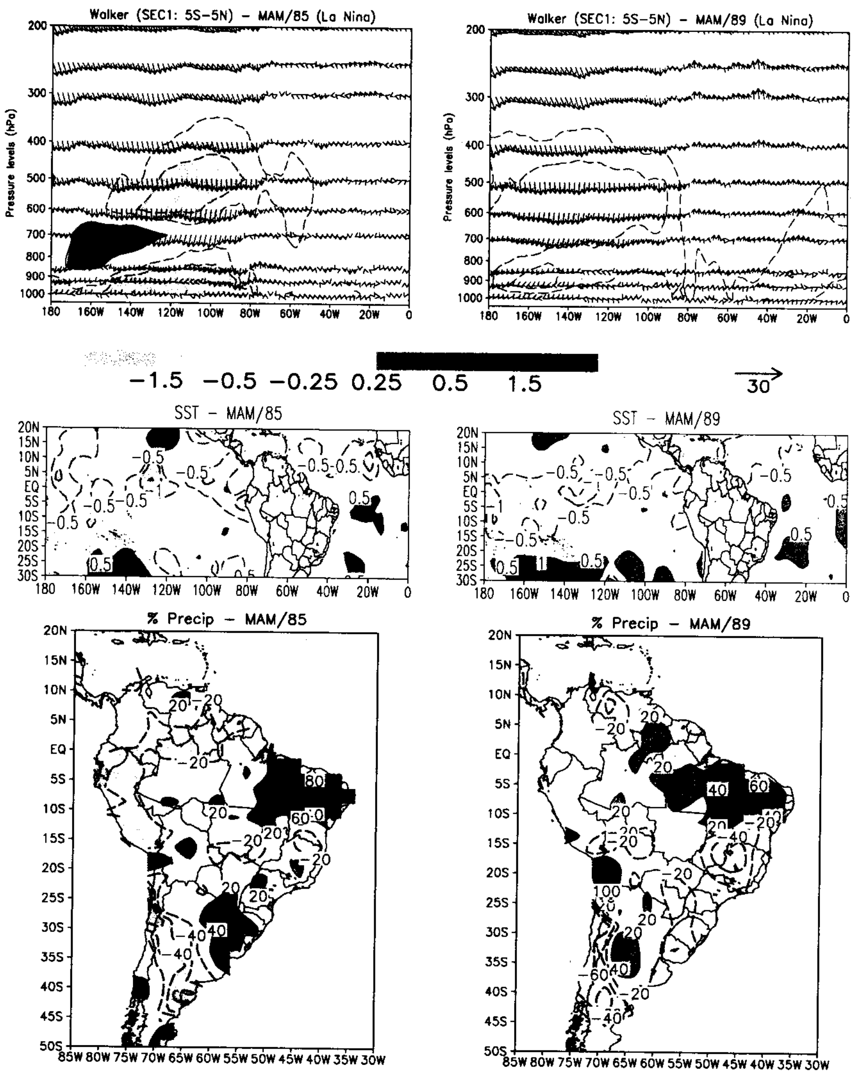

Fig. 8. As in Figure 5 but for the MAM period of the La Niña events observed in 1984-85 (left figures) and 1988-89 (right figures).

b. Hadley Cell during El Niño and La Niña

Figures 9 and 10 show the vertical structure of specific humidity anomalies and meridional (north-south) wind vector anomalies (meridional and vertical wind components) averaged in three latitudinal bands (SEC2, SEC3 and SEC4 schematized in the Fig. 3) for the 1982-83 (left figures) and 1986-87 (right figures) El Niño episodes, during DJF and MAM, respectively. An important feature observed in the SEC2 and SEC3 cross-sections are the predominance of negative anomalies of the vertical circulation acting over the north and northeast of South America, causing the inhibition of large-scale ascending movements related to the ascending branch of the Hadley cell. The areas affected by the occurrence of strong negative anomalies of precipitation, during the summer and autumn seasons, were Guyana, Surinam, French Guiana, center-east of the Amazon and the Brazilian Northeast. Inversely, over some South American subtropical areas centered approximately between 20°S and 30°S (where usually occurs the descending branch of the Hadley cell) positive anomalies of vertical circulation and specific humidity (SEC3 in the Figs. 9 and 10) are observed.

This circulation pattern might explain the positive precipitation deviation in some parts of the south and southeast of Brazil, Bolivia, Paraguay and northern Argentina in the DJF and MAM periods. Another interesting result observed in the SEC4 cross-section was the presence of positive anomalies of vertical circulation and specific humidity over the area between 10°S and 20°S, which indicates an intensification of the anticyclonic circulation, associated to the Bolivian High. Such intensification can influence the position of the upper tropospheric cyclonic vortice in the vicinity of Brazilian northeast and south tropical Atlantic (Kousky and Gan, 1981).

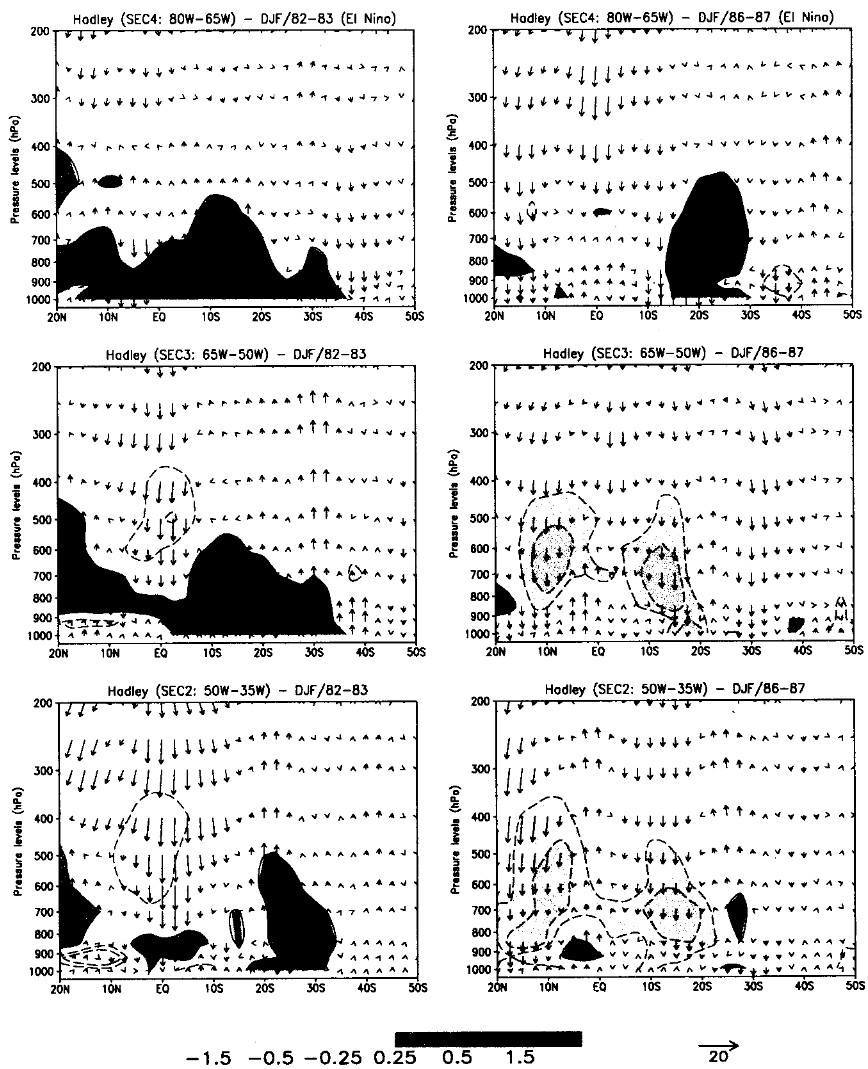

Fig. 9. Meridional vertical cross-sections (latitude x height) of the specific humidity anomalies (shaded contours in units of g/Kg) and east-west wind vector anomalies (arrows in units of Pa m/s), averaged between 50°W-35°W (SEC 2), 65°W-50°W (SEC 3) and 80°W-65°W (SEC 4). All fields refer to the DJF period of the El Niño events observed in 1982-83 (left figures) and 1986-87 (right figures).

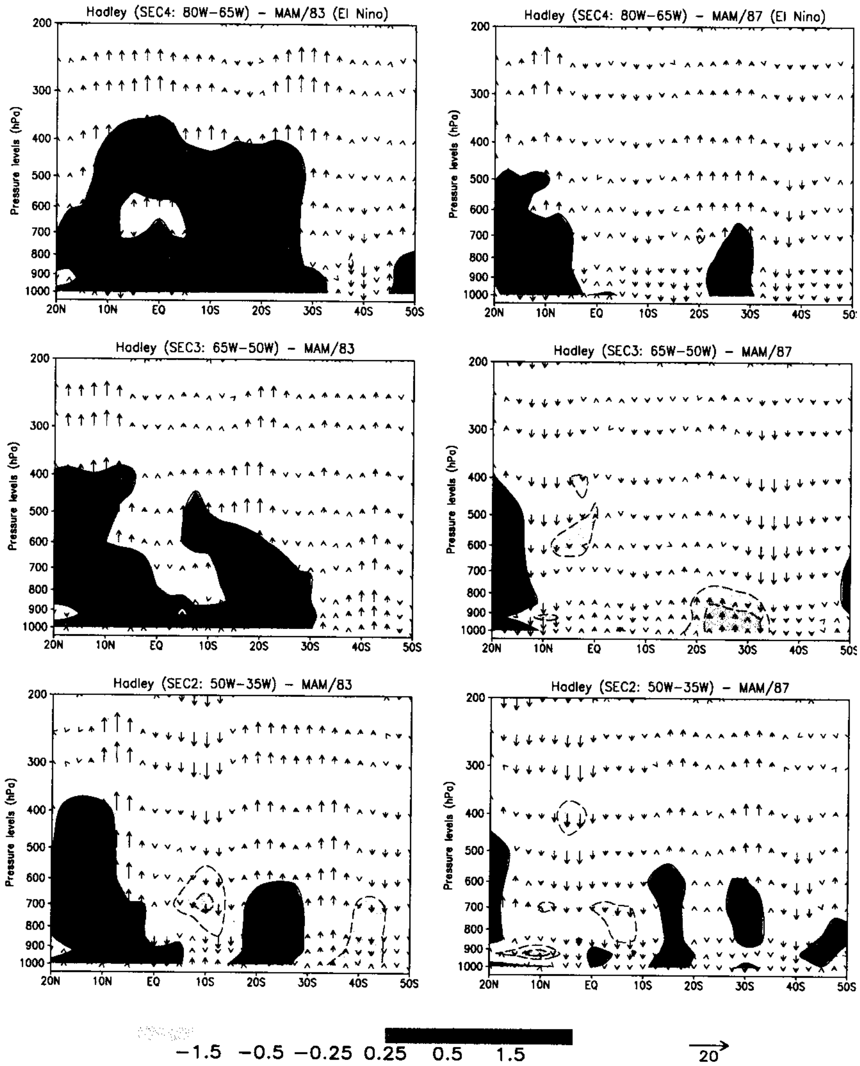

Fig. 10. As in Figure 9 but for the MAM period of the El Niño events observed in 1982-83 (left figures) and 1986-87 (right figures).

Similar analyses were done for the configurations of the Hadley circulation during the La Niña events of 1984-85 and 1988-89 (Figs. 11 and 12). In general, positive anomalies of ascending air from the tropical areas of South America (centered between 5°N and 20°S) and negative anomalies in the subtropical areas (centered between 30°S and 40°S) are observed. This pattern is associated to the enhancement of the ascending and descending climatological branches of the Hadley cell (see Fig. 4). Some areas, in particular in the Amazon and Brazilian northeast, show excess of precipitation, while the southeast and south regions of Brazil and parts of Paraguay and Argentina have deficit of precipitation. Another outstanding pattern observed in the SEC2 cross-section during the MAM period, was the formation of a thermally direct atmospheric meridional circulation cell with anomalous ascending branch between 5 to 10°S, including most of the Northeast Brazil and the tropical south Atlantic, where SST positive anomalies is observed, and an anomalous descending branch over the tropical north Atlantic, between 3 to 8°N, where there is negative anomalies of the SST.

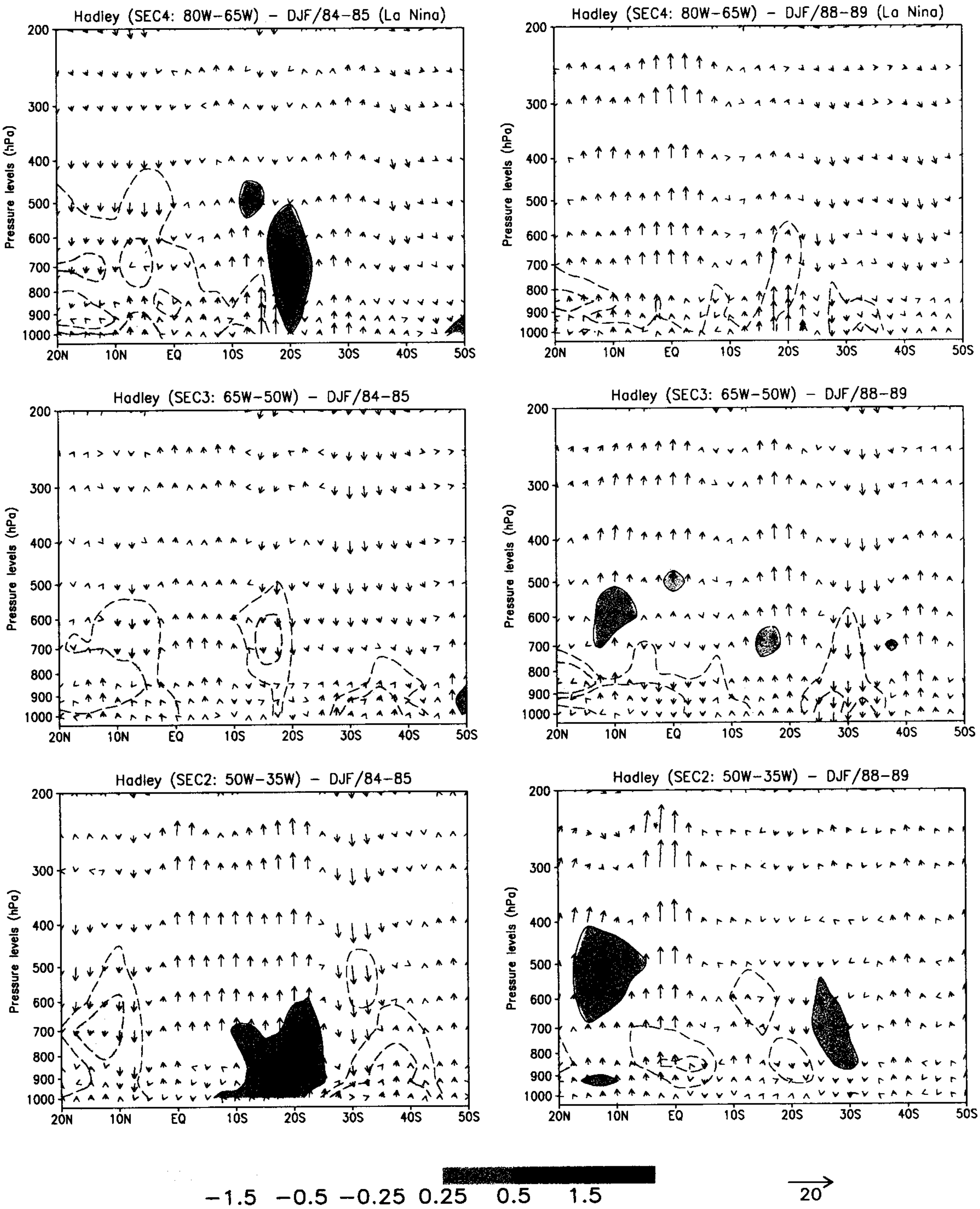

Fig. 11. As in Figure 9 but for the DJF period of the La Niña events observed in 1984-85 (left figures) and 1988-89 (right figures).

This anomalous meridional atmospheric circulation, associated to the SST anomalies pattern, known as the dipole pattern in the literature, has remarkable influence in the rainy season of the Northeast Brazil, as it was previously shown by Moura and Shukla (1981), Souza and Nobre (1998a) and Pezzi and Cavalcanti (2001).

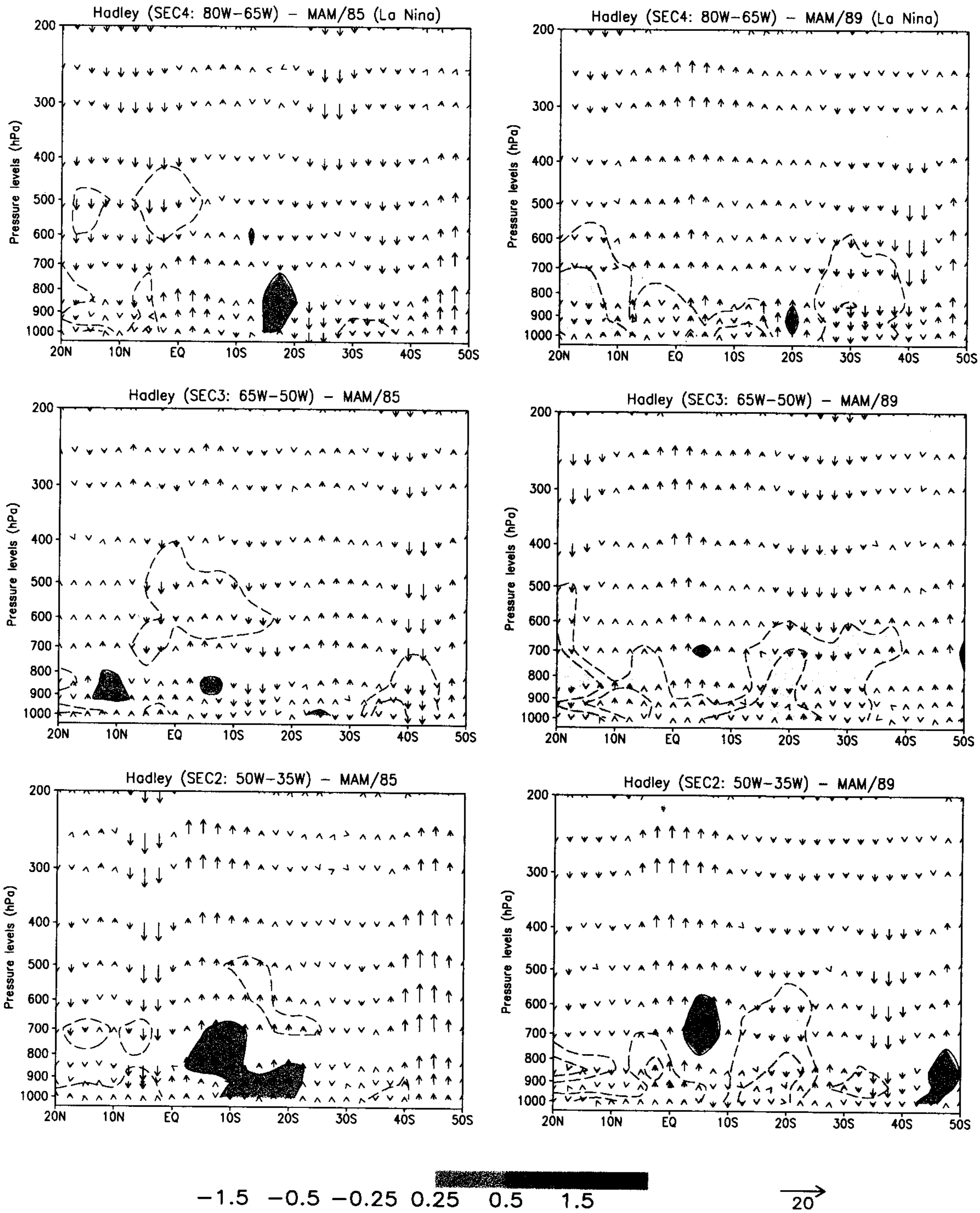

Fig. 12. As in Figure 9 but for the MAM period of the La Niña events observed in 1984-85 (left figures) and 1988-89 (right figures).

4. Concluding Remarks

The changes in the Hadley and Walker circulations and their respective impacts on the South American rainfall during the ENSO episodes observed in the decade of 80, were investigated through cross-sections analyses of the atmospheric circulation in altitude, averaged in the zonal and meridional directions.

The analyses for the 1982-83 and 1986-87 El Niño events showed that the Hadley and Walker circulations suffer dramatic changes, almost inverting their climatological circulation pattern. In these years, manifestation of the ascending branch of the Walker cell occurs over the center-east Pacific, while the descending branch affects most of the north-northeast of South America and equatorial South Atlantic. At the same time, we observe a significant weakness of the ascending branch of the Hadley cell over the South America tropics. The convective activity associated to ITCZ is inhibited due to the large scale sinking movement. This anomalous pattern causes drought conditions in the rainy seasons of the continental areas located to the north and northeast of South America, for instance, in the Guyana, Surinam, French Guiana, center-east of the Amazon and most of the Northeast Brazil. On the other hand, the conditions of excess of precipitation observed in the south-southeast of South America, were favored by the anomalous ascending branch of the Hadley cell (Fig. 9, SEC3). This feature is better observed during the 82/83 event. In fact, during the El Niño of 86/87, the Hadley cell circulation is reversed, diminishing the precipitation over the same region (Figs. 9, 10, SEC 3).

In La Niña events, we observed an intensification of the ascending and descending branches associated to the Walker and Hadley cells. During DJF of 84/85, the descending branch of the Walker cell was more intense than normal and extended from the dataline until 70°W in the northern part of South America. On the other hand, a large-scale anomalous ascending movement going from the Northeast of Brazil to the equatorial South Atlantic was observed. This pattern has probably favored the ITCZ to become more active than normal, resulting in a very abundant rainy season in these areas (Fig. 7). In the South America mid latitudes we noticed a very intense subsidence, which was probably responsible by the inhibition of the large-scale convection in the region. This pattern might explain the deficient rainy season observed in most of the south-southeast of South America (Fig. 11, 12, SEC 3).

The results showed in this study only refer to two episodes of each phase of ENSO; therefore any generalization should be taken with caution. However, it is our intention to extend these analyses to evaluate the changes in the Hadley/Walker circulations, associated to the ENSO events from other decades, in an attempt to identify the similarities and differences among the several events. A good understanding of the atmosphere circulation patterns during different ENSO episodes can be very helpful for the analysis of the results obtained from climate forecast models.

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REFERENCES

Aceituno, P., 1988. On the functioning of the Southern Oscillation in the South America sector. *Mon. Wea. Rev.*, **116**(2), 505-524.

Alves, J. M. B. and C. A. Repelli, 1992. A variabilidade pluviométrica no setor norte do Nordeste e os eventos El Niño-Oscilação Sul. *Rev. Bras. Meteo.*, **7**(2), 583-592.

Bjerknes, J., 1969. Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.*, **97**, 163-172.

Cane, M., 1992. Tropical Pacific ENSO modes: ENSO as a mode of coupled system. In: Trenberth, K. E. ed. *Climate System Modeling.* Cambridge University Press, Cambridge, p-583-614.

Casarin, D. P. and V. E. Kousky, 1986. Anomalias de precipitação no sul do Brasil e variações da circulação atmosférica. *Rev. Bras. Meteo.*, 1, 83-90.

Coelho, C. A. S., A. R. M. Drumond, T. Ambrizzi and G. Sampaio, 1999. Estudo climatológico sazonal da precipitação sobre o Brasil em episódios extremos da oscilação sul. *Rev. Bras. Meteo.*, **14**(1), 49-65.

Da Silva, A. M., C. G. Young and S. Levitus, 1994. Atlas of surface marine 1994. Algorithms and procedures. Washington, 1994. v.1, 83p. (NOAA ATLAS NESDIS).

Diaz, A. F., C. D. Studzinski and C. R. Mechoso, 1998. Relationships between precipitation anomalies in Uruguay and Southern Brazil and sea surface temperature in Pacific and Atlantic Oceans. *J. Climate,***11**, 251-271.

Figueroa, S. N., P. Satyamurty and P. L. Silva Dias, 1995. Simulations of the summer circulation over the South American region with an ETA coordinate model. *J. Atmos. Sci.*, **52**, 1573-1584.

Grimm, A. M., S. E. T. Ferraz and J. Gomes, 1998. Precipitation anomalies in Southern Brazil associated with El Niño and La Niña events. *J. Climate,* **11**, 2863-2880.

Hastenrath, S. and L. Heller, 1977. Dynamics of climatic hazards in Northeast Brazil. *Q. J. Roy. Meteo. Soc.*, **103**(435), 77-92.

Hastenrath, S., 1985. *Climate and circulation of the tropics.* D. Riedel, Dordrecht. 312 pp.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gardin, M. Iredell, S. Saha, G. White, J. Woolen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K-C. Mo, C. Ropelewski, A. Leetman, R. Reynolds, R. Jenne, 1996. The NCEP/NCAR reanalysis project. *Bull. Amer. Met. Soc.*, **77**, 437-471.

Kayano, M. T., N. J. Ferreira, and M. C. V. Ramírez, 1997. Summer circulation patterns related to the upper tropospheric vortices over the tropical South Atlantic. *Meteorol. Atmos. Phys.*, **64**, 203-213.

Kidson, J. W., 1975. Tropical eigenvector analysis and the Southern Oscillation. *Mon. Wea. Rev.*, **103**, 187-196.

Kouky, V. E. and C. Ropelewski, 1989. Extremes in the southern oscillation and their relationship to precipitation with emphasis on the South American region. *Rev. Bras. Meteo.*, **4**, 351-363.

Kousky, V. E. and M. A. Gan, 1981. Upper tropospheric cyclonic vortices in the tropical South Atlantic. *Tellus,* **33**, 538-551.

Kousky, V. E., I. F. A. Cavalcanti, M. T. Kayano, 1984. A review of the Southern Oscillation: oceanic-atmospheric circulation changes and related rainfall anomalies. *Tellus*, **36**A, 490-504.

Kousky, V. E. and M. A. Gan, 1981. Upper tropospheric cyclonic vortices in the tropical South Atlantic. *Tellus*, **33**, 538-551.

Moura, A. D. and J. Shukla, 1981. On the dynamics of droughts in northeast Brazil: observations, theory and numerical experiments with a general circulation model. *J. Atmos. Sci.*, **38**(7), 2653-2675.

Nobre, P. and J. Shukla, 1996. Variations of sea surface temperature, Wind stress and rainfall over the tropical Atlantic and South America. *J. Climate,* **10**(4), 2664-2479.

Nogués-Paegle, J and K-C. Mo, 1997. Alternating wet and dry conditions over South America during summer. *Mon. Wea. Rev.*, **107**, 279-291.

Pezzi, L. P. and I. F. A. Cavalcanti, 2001. The relative importance of ENSO and tropical Atlantic SST anomalies for seasonal precipitation over South America: a numerical study. *Clim. Dynamics*, **17**, 205-212.

Rao, V. B. and K. Hada, 1990. Characteristics of rainfall over Brazil: annuál and variation and connections with Southern Oscillation. *Theo. Appl. Climatol.*, **42**, 81-91.

Ropelewski, C and M. S. Halpert, 1987. Global and regional scale precipitation patterns associated with the El Niño-Southern Oscillation. *Mon. Wea. Rev.*, **115**(2), 1606-1626.

Souza E. B. and P. Nobre, 1998a. Uma revisão sobre o Padrão de Dipolo no Oceano Atlântico tropical. *Rev. Bras. Meteo.*, **13**(1), 31-44.

Souza, E. B., J. M. B. Alves and P. Nobre, 1998b. Anomalias de precipitação no norte e leste do Nordeste Brasileiro em associação aos eventos do Padrão de Dipolo observados no Atlântico tropical. *Rev. Bras. Meteo.*, **13**(1), 31-44.

Trenberth, K. E. and J. M. Caron, 2000. The Southern Oscillation Revisited: Sea level pressures, surface temperatures and precipitation. *J. Climate*, **13**, 4358-4365.

Uvo, C. R. B., C. A. Repelli, S. Zebiak and Y. Kushnir, 1998. The relationships between tropical Pacific and Atlantic SST and northeast Brazil monthly precipitation. *J. Climate*, **11**(4), 551-562.

Virji, H., 1981. A preliminary study of summer time tropospheric circulation patterns over South America estimated from cloud winds. *Mon. Wea. Rev.*, **109**, 599-610.

Xie, P. and P. A. Arkin, 1996. Analyses of global monthly precipitation using gauge observations, satellite estimates and numerical model predictions. *J. Climate*, **9**, 840-858.