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Interannual variability of high potential vorticity in South Atlantic

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Abstract

In this study, we examined intrusions of the high potential vorticity (HIGH-PV) at the 350 K isentropic level over the South Atlantic during the period December–January–February (DJF) 1979–2001. These events have a large interannual variability and are negatively correlated with the Southern Oscillation Index. Many events occur during the El Niño years except in 1997/1998, while there are none or few cases in La Niña years except in 1988/1989. The intrusion events which show interactions between the tropics and extratropics are associated with the 'westerly ducts' in the tropics and also with the amplitude of quasi-stationary waves and subtropical jet intensity. Copyright © 2011 Royal Meteorological Society

Keywords: potential vorticity; Rossby waves breaking; El Niño-Southern Oscillation

1. Introduction

The upper tropical troposphere presents regions of time-mean zonal winds (U_m) which can be easterly or westerly winds. The existence of regions of westerly U_m in the equatorial region may be related to large-scale atmospheric response to convective heating and also due to the regional heat distribution and sea surface temperatures (SST) in the tropical region (Arkin and Webster, 1985). Webster and Holton (1982) showed that the regions of westerly winds in the upper tropical troposphere act as 'ducts', which allow the transient Rossby waves to propagate between the tropical and extratropical regions. When these waves have large amplitudes, they break in the 'ducts' and act in the transport of atmospheric properties such as ozone between the tropics and subtropics.

The Rossby wave breaking (RWB) is characterized by rapid irreversible deformation of potential vorticity (PV) on isentropic surfaces (McIntyre and Palmer, 1983). This dynamic mechanism is responsible for the mixing of air masses with different characteristics and operates in the transport of water vapor and ozone between troposphere and stratosphere (Holton *et al.*, 1995; Scott and Cammas, 2002).

Waugh and Polvani (2000) studied the RWB events that resulted in stratospheric air intrusion into the tropical troposphere. They called 'intrusion events' (IE) the intrusion of high PV (HIGH-PV) at the 350 K isentropic level between 10 °S and 10°N in the upper troposphere. The IE occur in the Pacific and Atlantic oceans, especially during the austral summer and more frequently in the Pacific region. The IE have high impact on moisture and convection in the tropical region. Waugh (2005) observed a gradient of humidity close to these events, with dry air to the west and moist air to the east. Several authors reported the occurrences of deep convection to the east of IE, in which they observed low values of outgoing long-wave radiation (OLR) (Kiladis, 1998; Waugh and Funatsu, 2003; Allen *et al.*, 2009). Funatsu and Waugh (2008) showed that IE have an important role in destabilizing the lower troposphere, contributing to increase the convective available potential energy (CAPE) and provoke upward motion ahead of the PV tongue.

The IE also affect the rainfall over northeast of Brazil (NEB). Rao *et al.* (2007) showed that the interannual variation of IE, found by Waugh and Polvani (2000), over the South Atlantic Ocean (SAO) is negatively correlated with rainfall over northern NEB (NNEB). In years of high incidence of the IE, the precipitation anomalies in NNEB are negative and associated with cyclonic anomalies in the upper troposphere.

The IE have a great interannual variability in the Pacific Ocean and are strongly correlated with the phase of El Niño-Southern Oscillation (ENSO) (Waugh and Polvani, 2000), although less events occur in the Pacific during the warm phase (El Niño) of ENSO when compared with the cold phase (La Niña). The interannual variability of the IE is consistent with changes in U_m. Arkin and Webster (1985) observed that during the El Niño, the westerly winds in the upper troposphere of the equatorial region weaken or disappear in the eastern Pacific; however, the 'westerly ducts' in the Atlantic intensify. Thus, the interhemispheric teleconnection patterns in the Atlantic increase in magnitude during the El Niño events.

This work proposes a study of the interannual variability of HIGH-PV intrusions in the 350 K isentropic level over SAO. In addition, identifying the differences between the atmospheric patterns associated with those events during periods of El Niño (EN) and La Niña (LN) is also the focus of this work.

2. Data and methodology

2.1. Data

The analyses presented in this article are done for the period December–January–February (DJF) of the years 1979/1980 to 2000/2001. We used data from the reanalysis ERA-40 Project of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Uppala *et al*., 2005) at 1200 UTC with a spatial resolution of 1.125° × 1.125° longitude and latitude. The analyses considered the following meteorological variables: air temperature (K), wind fields (m s^{-1}) and monthly mean geopotential height Φ (m^2 s^{-2}). The Southern Oscillation Index (SOI) from National Oceanic and Atmospheric Administration (NOAA)-Climate Prediction Center (CPC) is provenienced from the website http://www.cpc.noaa.gov/data/ indices/soi

The monthly precipitation data, with a resolution of 2.5° × 2.5° longitude and latitude, are obtained from the Global Precipitation Climatology Project (GPCP) of the NOAA. Details of these data can be found in Huffman *et al*. (2001).

2.2. Methodology

PV is calculated from temperature and wind fields on isobaric levels, and then are interpolated to a 350 K surface according to Hoskins *et al*. (1985). The 350 K surface occurs near 200 hPa isobaric level at all latitudes (Tomas and Webster, 1994). The pattern of HIGH-PV is identified in the SAO using daily PV values. Many authors have used PV in the identification of RWB as well as in the incursion to lower latitudes (Tomas and Webster, 1994; Postel and Hichtman, 1999; Waugh and Polvani, 2000). In the present work we used days with contours of −1.5 PVU (1 PVU = 10^{-6} K m^2 s^{-1} kg^{-1}) which have an incursion into the tropics (∼10 °S) and occurred at four points of longitude grid (∼4.5°). The −1.5 PVU value represents the dynamic tropopause (Bluestein, 1993).

From the technique of empirical orthogonal function (EOF) applied to the PV field of days with −1.5 PVU in 10 °S it is possible to identify the patterns of HIGH-PV in the tropical SAO. This technique identifies the patterns of variability based on the magnitude and daily score for each component (Wilks, 2006). The EOF is applied to the area located between 50 °W and 0° and 30 °S and 0°. In this study, only the first mode (M1), which explains 17.5% of the variance, is used. The days with standard deviation scores greater than 1 ($1 \times \sigma$) are selected to analyze the interannual variability of the HIGH-PV events associated with M1.

The U_m average at 200 hPa $[U_m]$ is calculated in the tropical area of 35 °W to 10 °W and 10 °S to 10°N. The Pearson correlation between HIGH-PV events and $[U_m]$ is analyzed and its statistical significance is evaluated by the Student's t-test (significance level of 99%).

Cases of EN and LN are selected based on $0.5 \times \sigma$ average of DJF SOI. Composite fields of these EN and LN years are calculated to analyze the atmospheric patterns average. The composite variables are zonal wind at 200 hPa, PV at 350 K, geopotential at 200 hPa and precipitation. In addition, the geopotential is decomposed into the Fourier series to evaluate the stationary waves amplitude. The geopotential can be described as the sum of the component Φ_k:

$$\Phi_k = A_k(\varphi, p)\cos[k\lambda + \alpha_k(\varphi, p)] \quad (1)$$

$$\Phi = \sum_{k=1}^{n} \Phi_k \quad (2)$$

where k is the wavenumber ($n = 10$), A_k the amplitude, α_k the phase, p the pressure, λ the longitude and φ the latitude.

3. Results and discussion

The PV dominant pattern (M1) has opposite centers around NEB and over SAO (Figure 1(a)). The intrusions of HIGH-PV over SAO present incursions to lower latitudes, around 5 °S. The pattern founded is similar to the IE studied by Waugh and Polvani (2000).

According to the criterion of scores greater than $1 \times \sigma$, 124 events are selected for analysis of interannual variability of M1. Most events occurred in December (76 cases), followed by 27 cases in January and 21 in February. Waugh and Polvani (2000) also observed a higher incidence of IE in December over SAO. However, they did not discuss the connection with ENSO. Higher incidence of events in EN years and the opposite in LN years are identified over SAO (Figure 1(b), bars). The correlation coefficient between the average SOI and the number of events is −0.58, statistically significant at 99% level. This means that more events occur in EN than in LN.

The interannual variability of HIGH-PV events is consistent with that of interannual variability of $[U_m]$ at high levels (Figure 1(b), solid contours). $[U_m]$ is positive in all years, indicating that westerly winds occur in the austral summer of the equatorial SAO. This result is consistent with the climatology of Tomas and Webster (1994). It is observed that in EN (LN) years, the westerly wind in the equatorial region is intense (weak). The correlation between SOI and $[U_m]$ is −0.80 (significance of 99%). This shows the connection between the SOI and the intensity of the equatorial 'westerly duct'. Webster and Holton (1982) showed that the range of tropical–extratropical interaction depends strongly on the magnitude of the westerlies in the region of equatorial 'ducts'. The correlation between the number of events and $[U_m]$ is

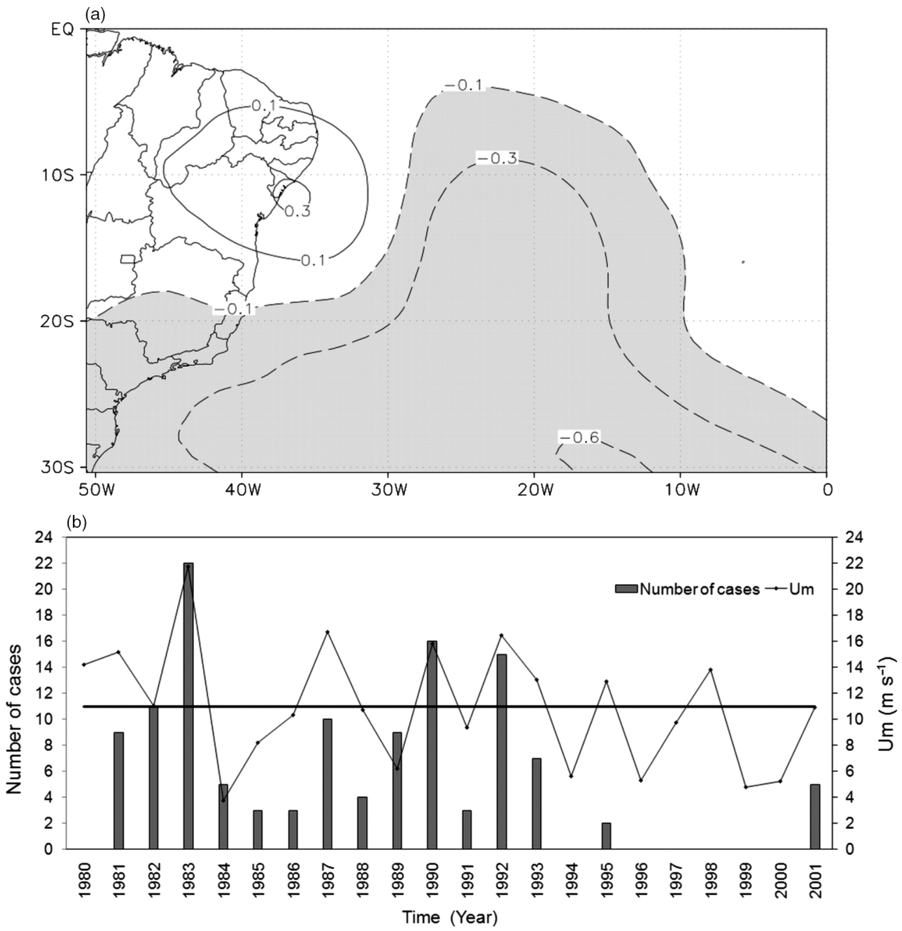

Figure 1. (a) Spatial pattern ('loading') of M1. (b) Number of cases of HIGH-PV (bar) and $[U_m]$ (continuous contour) in each year. The solid line represents the average of $[U_m]$ (11 m s^{-1}).

0.68 (significance of 99%). This indicates that strong westerly U_m favors more intrusions. It is also noted that there are no cases of intrusion from 1996 to 2000, and during this period only 1997/1998 presented $[U_m]$ slightly above average.

According to the criterion of the SOI less/greater than $0.5 \times \sigma$, 10 years are selected to analyze the differences in atmospheric patterns between EN and LN years (Table I). The selected EN years show a large number of HIGH-PV events in the tropical region, except for the year 1997/1998. The opposite is observed in LN, little or no occurrence of the events, except for the year 1988/1989. The $[U_m]$ is intense (weak) in these EN (LN) years, as noted earlier. To try to explain these anomalous occurrences, the years 1997/1998 and 1988/1989 are analyzed separately and compared with the composite of EN (CEN) and LN (CLN). The selected years for the CEN are 1982/1983, 1986/1987, 1989/1990 and 1991/1992 and the CLN are 1996/1997, 1998/1999, 1999/2000 and 2000/2001.

Table I. Years with highest negative and positive 0.5σ of the SOI.

	Year	NE	$[U_m]$	SOI
El Niño	1982/1983	22	21.8	−6.4
	1986/1987	10	16.7	−2.5
	1989/1990	16	15.8	−1.8
	1991/1992	15	16.4	−3.9
	1997/1998	0	13.8	−4.0
La Niña	1988/1989	9	6.2	2.2
	1996/1997	0	9.7	1.6
	1998/1999	0	4.8	2.2
	1999/2000	0	5.2	2.1
	2000/2001	5	10.9	1.8

NE, number of events; $[U_m]$, mean zonal wind; SOI, Southern Oscillation Index.

Figure 2(a) shows the average field of PV in the 350 K isentropic level and zonal wind at 200 hPa for the CEN. The values of −1.0 −1.5, −2.0 and −2.5 PVU are solid dark lines. There are high values of PV (−1.5 PVU) extending toward the tropical region near 25 °W, forming a 'tongue' of HIGH-PV northwest–southeast. This incursion of HIGH-PV in the tropics occurs in the vicinity of the western equatorial 'ducts'. The U_m at 10 °S has values exceeding 10 m s^{-1} between 40 °W and 20 °W. Arkin and Webster (1985) observed that in EN years there is an intensification of U_m in the region of the 'westerly ducts' over the equatorial SAO, favoring the propagation of waves between the extratropics and tropics. However, in 1997/1998 (Figure 2(b)) only the incursion of PV −1.0 PVU is observed toward the tropics and the U_m in the tropical region is nearly 10 m s^{-1}.

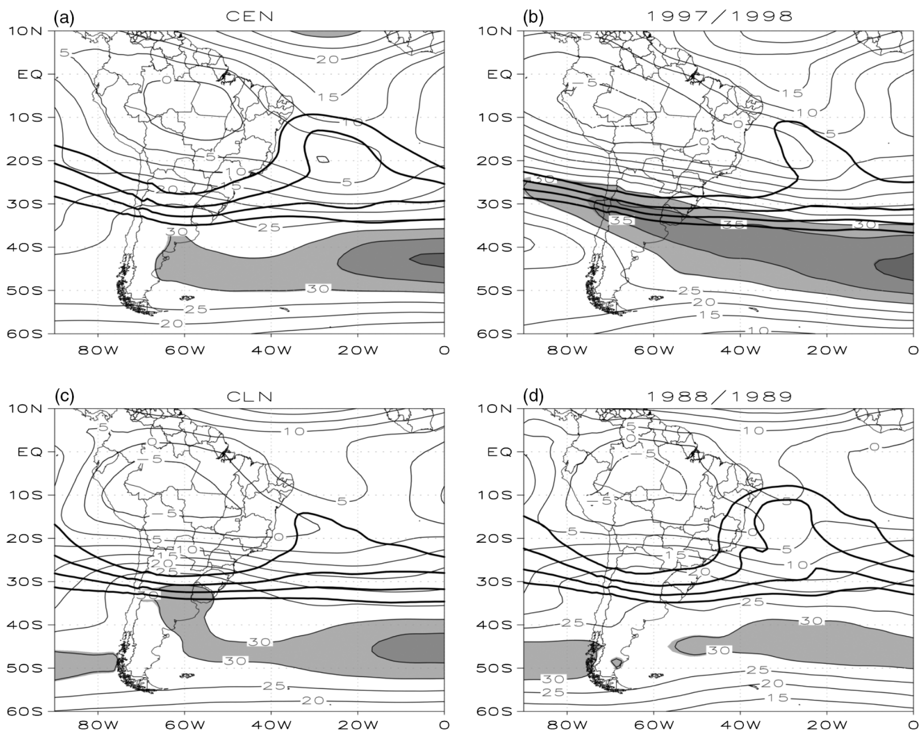

Figure 2. PV on isentropic level of 350 K (thick solid line). Values of −1, −1.5, −2.0 and −2.5 PVU. U_m at 200 hPa (thin solid line). Magnitude of wind above 30 m s^{-1} (shaded), representing the subtropical jet. (a) CEN, (b) 1997/1998, (c) CLN, and (d) 1988/1989.

The CLN (Figure 2(c)) shows a contour deformation of −1.0 PVU and the equatorial U_m is around 5 m s^{-1}, similar to the climatology. In 1988/1989 (Figure 2(d)), an incursion of HIGH-PV (−1.5 PVU) can be observed toward the tropics, reaching 10 °S. That event also features a northwest/southeast tilt in the contours of PV and U_m in the tropical region is also weak. In the analysis of ENSO cases, U_m in the equatorial region indicates the presence of 'westerly ducts', a favorable condition for wave propagation toward the tropics. EN events presented an increase of U_m in the equatorial region, while in the events of LN there are climatological values. Therefore, U_m behavior alone does not explain the number of HIGH-PV in inter-ENSO cases and another factor may also be important to explain this variability and favor the propagation of waves between the extratropics and the tropics.

The differences in ENSO teleconnections are related to the phase of the forced stationary Rossby waves (Hoerling *et al*., 1995; Magaña and Ambrizzi, 2005). These authors noted that the phase and amplitude of these waves are associated with the structure of the zonal flow and the anomalous convective forcing in the Pacific. The magnitude of the wind above 30 m s^{-1}, representing the subtropical jet (STJ), is seen in Figure 2 (shaded region). The STJ is intense (weak) in EN (LN) years. However, it is observed that in the year 1997/1998 the STJ is more intense when compared with CEN. On the other hand, in 1988/1989 the STJ is weaker than in CLN. These differences in intensity of the STJ affect trajectories followed by the planetary waves triggered by the equatorial heat sources (Magaña and Ambrizzi, 2005).

The amplitude of wavenumbers 1 and 2 (Figure 3) are below (above) average in the years of EN (LN). However, it is interesting to note that the amplitude of wavenumber 3 is higher in CEN and in 1988/1989. In cases of 1997/1998 and CLN the amplitude of this wavenumber is smaller and closer to the average, respectively. Magaña and Ambrizzi (2005) showed that zonal wavenumber 3 better adjusts to the quase-stationary waves in the SH in 1997/1998. It is suggested that the amplitude of these waves is not large enough to penetrate the tropical region in 1997/1998 and CLN.

Geopotential anomalies at 200 hPa and precipitation anomalies are shown in Figure 4. A cyclonic anomaly on the tropical SAO can be observed in years with more HIGH-PV events (CEN and 1988/1999), which contributes to the intrusion of these events. (Figure 4(a) and (d)). In 1997/1998 and CLN (Figure 4(b) and (c)), the SAO tropical region is dominated by an anticyclonic anomaly, which is not favorable for the intrusions.

In CEN, positive precipitation anomaly is observed over the southern NEB (SNEB). Although it is known that in EN years the precipitation anomaly is negative over the NEB (Ropelewski and Halpert, 1987), this influence is seen only in the northern sector of Brazil, including NNEB, in DJF. In Figure 4, the reduced precipitation in the intertropical convergence zone (ITCZ) region is identified in both CEN and 1997/1998. From the observed atmospheric patterns, the positive precipitation anomalies in CEN are related to the presence of the cyclonic vortices over SAO. In 1988/1989 there is positive precipitation anomaly in the western side of

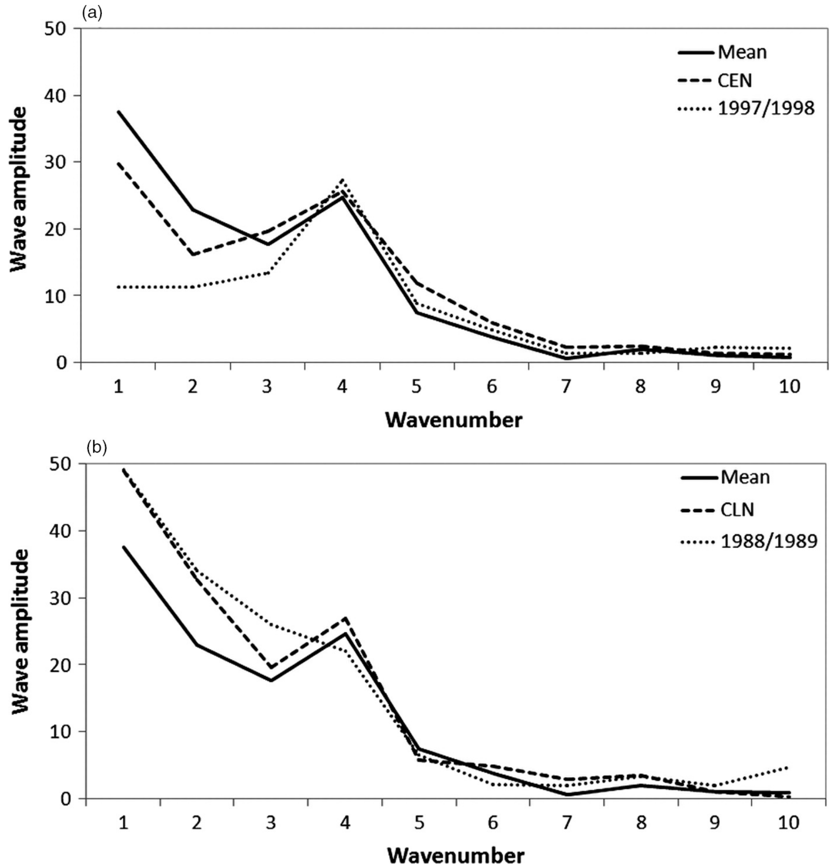

Figure 3. Amplitude of waves at 200 hPa around 20 °S. Solid line represents DJF average amplitude for the entire period. (a) Magnitude of CEN (dashed line) and 1997/1998 (dotted line); (b) magnitude of CLN (dashed line) and 1988/1989 (dotted line).

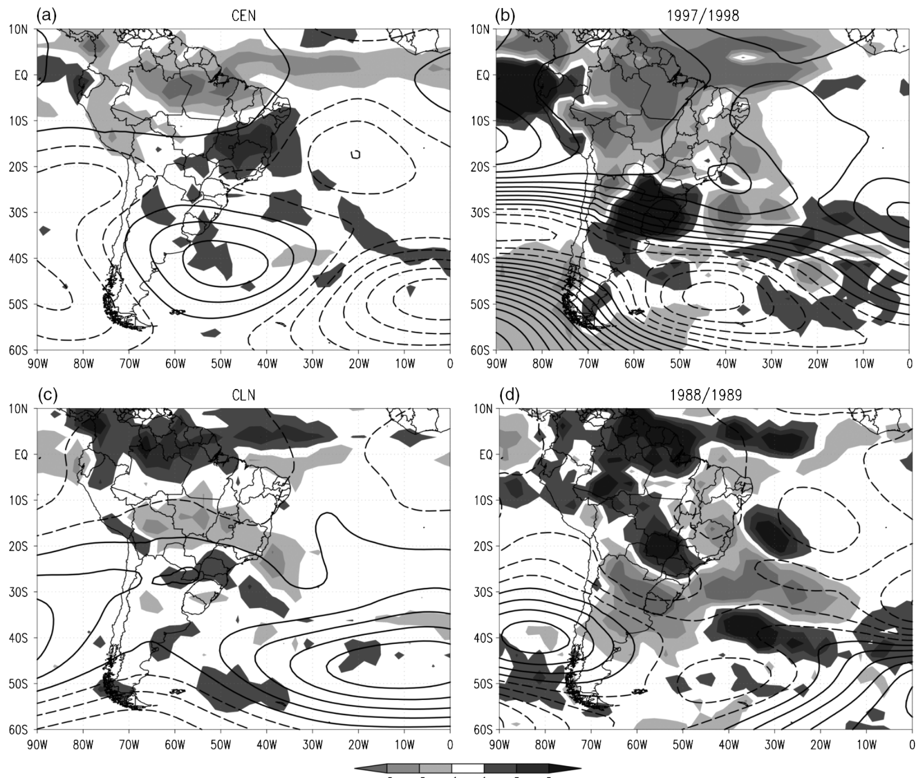

Figure 4. Anomaly of geopotential at 200 hPa (contours) in $m^2\ s^{-2}$ and anomaly of precipitation (shaded) in mm day^{-1}. Geopotential negative values are dashed and the range is 10 $m^2\ s^{-2}$, starting at 5 $m^2\ s^{-2}$. (a) CEN, (b) 1997/1998, (c) CLN and (d) 1988/1989.

the cyclonic anomaly, although not reaching the continent. These patterns are consistent with Kousky and Gan (1981) who identified convection associated with upper level cyclonic vortices (ULCV) in the western portion of these systems. Wind divergence (Figure not shown) analysis showed divergence over the region, favoring upward motion and precipitation over SNEB. Over NNEB, the precipitation anomaly is negative, agreeing with Rao *et al*. (2007). In this region, there is convergence of the winds at high levels, causing subsidence and inhibiting convection. In CLN and 1997/1998 the lack of IE and ULCV explains the reduced precipitation over or close to the NEB. The impact of LN in DJF is seen in the ITCZ higher than normal precipitation (CLN and 1988/1989).

The correlation between the precipitation anomaly and the number of HIGH-PV events is positive in the SNEB and negative in the NNEB. In years with more IE over SAO there are positive precipitation anomalies over SNEB and negative anomalies over NNEB. Therefore, besides the large-scale ENSO impact on NEB precipitation, synoptic scale ULCV associated with intrusion events can produce precipitation anomalies in the region.

4. Conclusions

This study examined the interannual variability of the HIGH-PV intrusions at the 350 K isentropic level over the tropical SAO. The events of HIGH-PV show a great interannual variability and are significantly correlated with SOI (correlation −0.58). This indicates that EN years have a higher number of events and the opposite occurs in LN years. The U_m in the tropical region is consistent with this result, because in EN years U_m is intense and form 'westerly ducts' with winds exceeding 10 m s^{-1}. In LN years, the 'westerly ducts' are weaker, with U_m around 5 m s^{-1} in the tropical region.

There is an inter-ENSO variability in the occurrence of HIGH-PV events. The EN and LN years are selected according to the criterion of the SOI less/greater than $0.5 \times \sigma$. Many events of HIGH-PV are observed in CEN and no event occurred in 1997/1998, also an EN episode. The CLN has few or no intrusion of HIGH-PV, while in the year 1988/1989 many events occurred. There were intense westerlies U_m in the equatorial region in the CEN and 1997/1998, while during the CLN and 1988/1989, the zonal winds were weaker. The presence of 'westerly ducts' is important for the interaction between tropics and extratropics. However, it is necessary that waves have amplitudes large enough to penetrate into the tropical region.

The events in 1997/1998 and CLN are associated with intense STJ, which act as a barrier to the propagation of quasi-stationary waves over the SAO. Another important factor is the amplitude of the zonal wavenumber 3 that is small in 1997/1998 and CLN. In the CEN and 1988/1989, the amplitude of this wave is large enough to break over SAO. It is suggested that in addition to westerly winds in the tropical Atlantic, the amplitudes of quasi-stationary wave and intensity of STJ are also important for the interaction extratropics–tropics.

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