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INTRASEASONAL MODES OF VARIABILITY AFFECTING THE SOUTH ATLANTIC CONVERGENCE ZONE

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ABSTRACT

The intraseasonal variability of the South Atlantic Convergence Zone is investigated applying statistical techniques to the daily NCEP/NCAR reanalysis data set and the daily-interpolated NOAA satellites OLR, both ranging from 1979 to 1999. The data were filtered to retain frequency fluctuations between 30 and 90 days. The intrinsic connection among tropical convection in the Indonesian region, the subtropical flow and the convection in the South Atlantic Convergence Zone (SACZ) is discussed. The analyses are consistent with previous suggestions of the influence of Madden-Julian Oscillation (MJO) on tropical South American convection and studies of the Pacific South American (PSA) wavetrain role on SACZ. In the present study, the two dominant intraseasonal modes of variability affecting the SACZ are discussed on the basis of a zonal mode (the Madden-Julian Oscillation) and a tropical-extratropical mode (Pacific South American Pattern). The opposite convective behaviour between Indonesia and tropical South America is discussed, as well as the connection between SACZ convection and PSA-like pattern. It was noticed that an SACZ episode occurring in the northernmost position can be influenced by the MJO, and can trigger a wavetrain over the South Atlantic and Indian Ocean, while positions further south can be influenced by a tropical-extratropical PSA-like wavetrain. High-frequency (2–10 days) analysis displayed dominant wavetrain patterns of shorter wavelength than the intraseasonal wavetrain, but with similar characteristics, over South America, indicating the influence of synoptic systems, like frontal zones, over the continent. It is suggested that when these two frequencies, high (frontal systems) and intraseasonal (MJO or PSA), are in phase, they are able to establish appropriate conditions for an SACZ episode development. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: intraseasonal; SACZ; PSA; MJO

1. INTRODUCTION

The South Atlantic Convergence Zone (SACZ) episodes are important contributors to the amount of seasonal precipitation observed during the austral summer, mainly over southeastern and central Brazil. Episodes of persistent rainfall over southeastern Brazil related to the SACZ occurrences have been associated with the interaction between tropical convection over South America and displacement of frontal systems from higher latitudes. Monthly atmospheric monitoring in Climanalise Bulletin (www.cptec.inpe.br/products/climanalise) has shown that SACZ events occur when frontal systems reach tropical/subtropical regions of South America and interact with tropical convection. Siqueira and Machado (2003) documented such interactions by analysing satellite images.

Southeast Brazil is the most industrialized and populated region of the country and, consequently, a region that is highly vulnerable to adverse social and economic impacts due to extreme precipitation events. Excessive rainfall causes landslides near the highly populated coast and floods in urban areas. This region is also a major

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source for hydroelectric power generation, which can be affected by droughts. A severe drought occurred during the 2000–2001 summer, which led to a general shortage of water and energy (Cavalcanti and Kousky, 2001). During that season, there were no SACZ episodes.

Kodama (1992) showed that the SACZ has features that are similar to those of the South Pacific Convergence Zone (SPCZ), such as the south-eastward extension of the cloudiness band into the subtropics, the formation along the upper subtropical jet in the eastern part of the trough that penetrates into the subtropics, the occurrence of large low level moisture gradient and the relation to the tropical monsoon convection and subtropical highs. Casarin and Kousky (1986) suggested that a convective episode of the SPCZ could be related to an SACZ episode – after the former had been established, the latter would be triggered within 15 days – suggesting a propagation mechanism such as the Madden-Julian Oscillation (MJO). Kalnay *et al.* (1986), investigating a stationary wave that crossed the South American continent during January 1979, also found correlations between the SPCZ and the SACZ. Working with a simple barotropic model and influence functions, Grimm and Silva Dias (1995) observed that anomalous convection in the SPCZ region, associated with the natural cycle of the MJO, was able to influence the convection over the SACZ region through the strengthening of a trough at high levels.

Over the Pacific Ocean in the austral winter season, a quasi-stationary wave pattern was identified by Mo and Ghil (1987), which they named *Pacific South American (PSA)* pattern because of its resemblance to the Pacific North American (PNA) pattern. Mo and Higgins (1998) associated such a pattern with the main winter modes of intraseasonal variability in the Southern Hemisphere. The PSA was identified in the streamfunction variability as two modes of low frequency characterized by a wave number 3 and oscillating in quadrature. When considered together, those two modes represent the intraseasonal oscillation of the upper circulation in the Southern Hemisphere with periods of roughly 40 days. The PSA modes are striking patterns that appear in many data sets and data periods, and represent the main modes of variability of the anomalous upper flow in the intraseasonal band in the austral winter (Mo and Ghil, 1987; Mo and Higgins, 1998; Kidson, 1999; Cavalcanti, 2000) and in the austral summer (Mo and Paegle, 2001).

Over the equatorial Indian and Pacific regions, it is well known that one mode of intraseasonal variability that occurs at periods of 30 to 60 days is associated with a global scale cell of zonal circulation that runs through the equatorial belt – the MJO (Madden and Julian, 1972). Influences of this oscillation on tropical convection over South America during the austral summer season were discussed in Weickmann *et al.* (1985), Kousky and Kayano (1994) and Kiladis and Weickmann (1992). Mo and Paegle (2001) analysed climate variability in the intraseasonal band (10–90 days) and discussed the relation between tropical convection, the MJO and PSA pattern modes. They conclude that the PSA1 mode was modulated by the tropical intraseasonal oscillation dominated by the MJO.

The objective of this study is to analyse features of SACZ intraseasonal variability, the low- and high-frequency modes of convective variability over South America and the influence of teleconnections in the tropical and extratropical regions on SACZ convection. Section 2 outlines the data and methods utilized. The third section presents the results obtained from cross correlations, empirical orthogonal functions (EOF) and composite techniques. Section 4 contains the summary and conclusions.

2. DATA AND PROCESSING TECHNIQUES

Daily zonal and meridional wind at 200 hPa from NCEP/NCAR reanalysis (Kalnay *et al.*, 1996) and daily NOAA-OLR data sets (Liebmann and Smith, 1996) were analysed from 1979 to 1999 (November to March). The meridional wind was used as a proxy for the wave flow and the OLR was utilized as a proxy for convective rainfall. Both data sets have a resolution of 2.5° latitude $\times$ longitude.

The daily anomalies were calculated considering the daily climatologies for each grid point obtained from the linear interpolation of monthly climatological means to 365 values. The anomalies of meridional wind and outgoing long wave radiation will be referred hereafter simply as VWND and OLR, respectively. The daily anomalies were filtered using the Lanczos filtering (Duchon, 1979). The filter was applied to retain two bands of frequencies, low frequencies (30 to 90 days) that are related to intraseasonal variability and high frequencies (2–10 days) that are related to synoptic systems. The filter was 70-days weighted for both bands of frequencies.

The methods to investigate teleconnections were (Pearson product-moment) correlation between key areas and gridpoints over the globe, EOF of the covariance matrix and composition of global fields for extreme events. The EOF technique was applied to identify the main patterns of intraseasonal variability and to enhance the areas of large variance of convection (OLR) and atmospheric wave behaviour (VWND). This technique was used considering two domains, one comprising the South American Continent and the other including the South Pacific Sector, Indonesia and parts of the Indian Ocean. As a complement, correlation analysis using filtered data (30 to 90 days) in the intraseasonal band was performed considering an area in the Indonesian region, which is one of the most convective areas in the tropical belt, as seen in Kiladis and Weickmann (1992), and areas in the SACZ region. The first area ranges from 114 °E to 164 °E and from 14 °S to 9 °N, representing the area of enhanced convection, hereafter referred as INDO. Three diagonally oriented areas named *SACZ1, SACZ2* and *SACZ3* over South America are intended to represent the most likely positioning of an SACZ event in the correlation analysis. SACZ1 would represent an event displaced to the north of its climatological position, SACZ2 corresponds to the climatological position and SACZ3 would be the representation for an event displaced southward. These areas are indicated in Figure 1.

The correlations were performed between the area averaged OLR values for each selected area, and the OLR and VWND values at all grid points. Both variables were filtered in the 30–90 days band. The aim was to determine significant linear relations in space associated with convection in the selected areas. The correlations were calculated with lags (stepping each 5 days) to identify temporal relations as well. The statistical significance assessment of the cross correlation analysis was performed using Student's T-test, considering the degrees of freedom according to Kreyszig (1970). After each gridpoint had passed the individual significance test, it was also submitted to a test of field significance. Following the method described in Livezey and Chen (1983), the binomial distribution was applied, and it was found that 186 or more gridpoints are needed to pass the individual tests to guarantee that the 95% level of confidence had not been achieved only by chance. All correlation maps (for the four areas, with all lags and with both variables, VWND and OLR) contain more than 186 gridpoints that satisfy the individual test of significance. In other words, the patterns are not due to chance.

To discuss aspects of teleconnections associated with SACZ convection, composite analysis based only on strong convective events over South America was performed. The data set used to choose and perform the composites was filtered in the 30–90 days band. Strong events were characterized according to the quartile criteria for OLR because it is a resistant measure, i.e. discards previous assumptions about the nature of the data set. The first quartile threshold was -7.1 W m^{-2} for SACZ1 and -7.3 W m^{-2} for SACZ2. SACZ3 area has a distribution very similar to SACZ2 area. Strong events were defined as sequences of days with the area averaged value of negative anomalous OLR below the first quartile threshold. For each event, mean OLR anomalies were computed by averaging over the duration of that event. The total composites were obtained by averaging all events.

One example of the influence of low (intraseasonal) and high (synoptic) frequency on the SACZ episodes is shown for a period on the basis of the expansion coefficients of EOF analysis over the South American sector (filtered 30–90 days OLR). The filtered data in the two frequency bands (30–90 days and 2–10 days) and the non-filtered data were analysed for this period.

3. LOW- AND HIGH-FREQUENCY OLR VARIABILITY OVER SOUTH AMERICA

In the last decades, many studies have shown that during summer the convective activity tends to be organized in a north–south dipole of enhanced-suppressed convection over South America (Casarin and Kousky, 1986; Kousky and Cavalcanti, 1988; Kousky and Kayano, 1994; Nogues-Paegle and Mo, 1997; Chaves and Cavalcanti, 2001). In the current study, low-frequency (intraseasonal) and high-frequency (2–10 days) loadings display similar behaviour (Figures 1 and 2). The percentage of the total variance explained by the four first loadings in the intraseasonal band is 63.4%, with 28.5, 16.8, 11.5 and 6.6 being the individual fractions

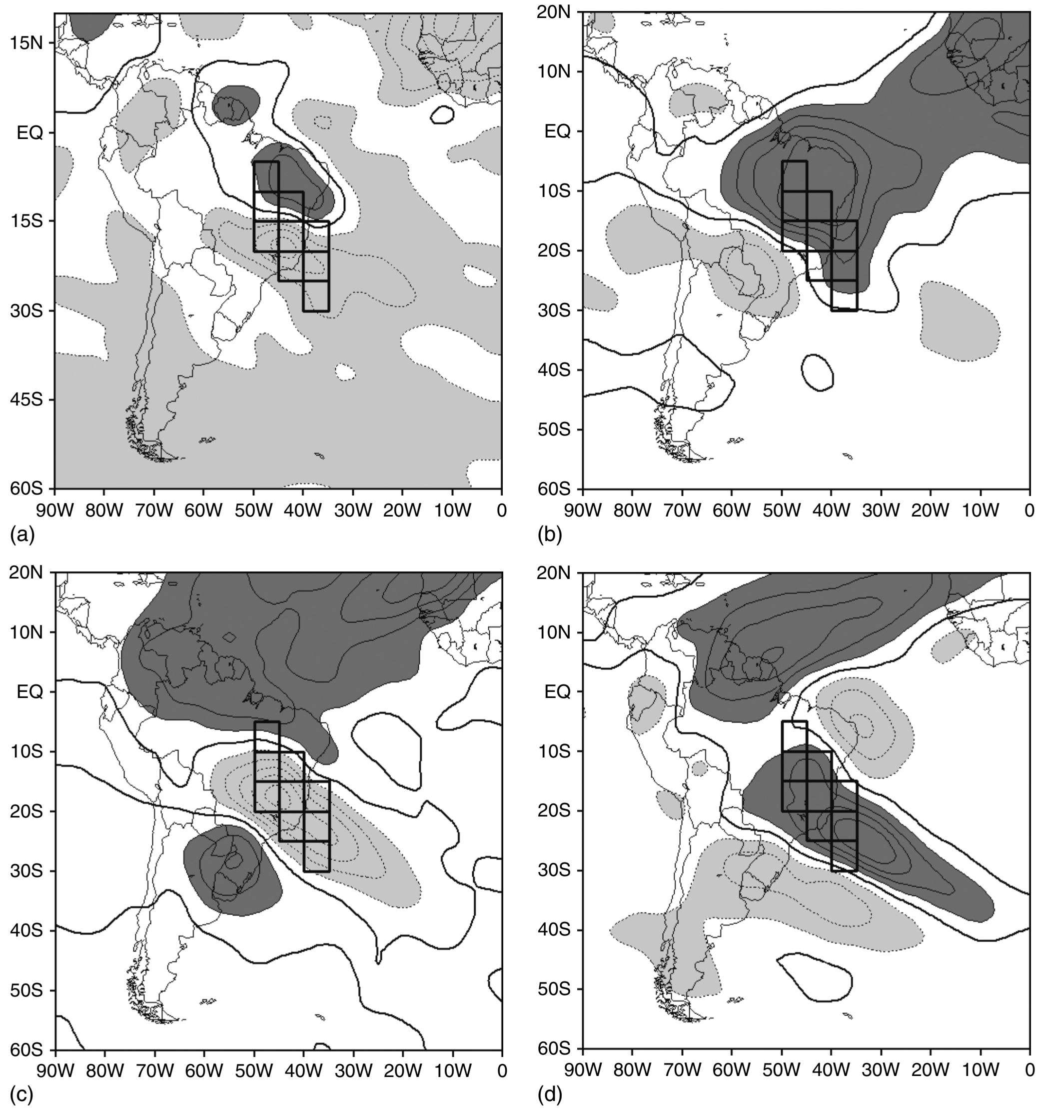

Figure 1. EOF loadings for 30–90 days OLR variability over South America. (a) First loading; (b) second loading; (c) third loading; (d) fourth loading; light (dark) shadings are negative (positive) loadings greater than −2 (+2) $W^2.m^{-4}$. Contour interval is 2 and the thick line is zero

explained by the first, second, third and fourth loadings, respectively. The intraseasonal EOF loadings of OLR show basically an opposite relation between tropical and subtropical South America, indicating the tendency for a see-saw behaviour of convection in South America (Figure 1). In this timescale, the patterns show dipoles of convection between northeast and southeast Brazil (EOF1) and between north/northeast Brazil and southwest Brazil/Paraguay (EOF2). The EOF3 and EOF4 display opposite centres to the north and south of the SACZ area and elongated patterns oriented NW-SE, extending over subtropical South Atlantic, typical of the SACZ configuration. Considering the diagonal boxes, EOF1 would represent the SACZ displaced southward, EOF2 displaced northward, and EOF3 and EOF4 in the climatological position. Kousky and Kayano (1994) found a pattern of OLR variability similar to the EOF2. Analysing the temporal evolution, they concluded that such configuration could be related to the Madden and Julian Oscillation acting on the tropical region of South America.

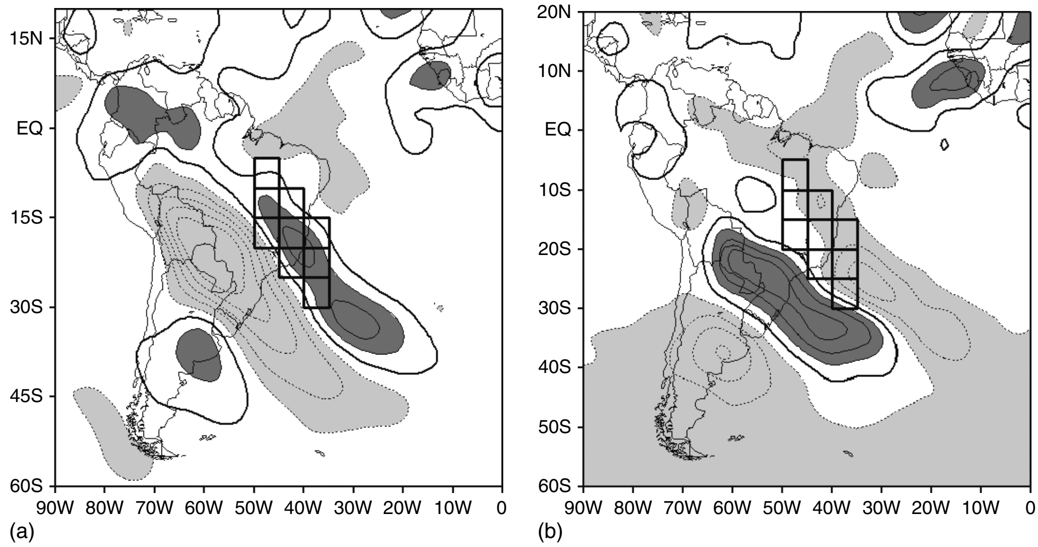

Figure 2. Same as Figure 1 for 2–10 days OLR variability. (a) First loading; (b) second loading

The high-frequency patterns of OLR (Figure 2) also present NW-SE elongated areas of variability, capturing the characteristics of frontal systems over South America. They represent 13.1% (first loading) and 12.5% (second loading) of the total variance found in the high-frequency band. The alternating signs of convection are related to the ascending motion along and the subsidence behind frontal systems. Cavalcanti and Kayano (1999), investigating the main patterns of high-frequency variability considering the meridional component of wind, found wave trains crossing the extratropical South Pacific and bending over South America. They suggested that such wave trains could be the representation of wave pulses from frontal systems and might be responsible for maintaining the convective activity in the SACZ. Liebmann *et al.* (1999) also showed that Rossby waves arising from the extratropical belt could be modulating convection in the SACZ in the submonthly scale (2–30 days). Analysing infrared satellite data, Siqueira and Machado (2003) studied the interaction between tropical convection and frontal systems, showing the influence on SACZ occurrences.

Figure 3 exemplifies how different bands of variability can be connected in a SACZ episode. Figure 3(a) is the average of anomalous OLR filtered in the 30–90 days band during an extreme event (11/22/1984 to 11/26/1984), obtained from the expansion coefficients of the third PC over South America (Figure 1(c)). Extreme events were defined when the values of the PC-3 were larger than 0.8 of its standard deviation. The third PC and Figure 3(a) exhibit a pattern that is typically associated with the SACZ occurrence – enhanced precipitation over southeastern Brazil and decreased rainfall in areas to the south. The unfiltered anomaly also shows convection in a NW-SW band over the southeastern coast of Brazil, and lack of convection to the south, indicating the occurrence of an SACZ episode (Figure 3(b)). High frequency anomalous patterns during this period (Figure 3(c) to (e)) show features of a frontal system displacement over South America. Therefore, high and intraseasonal frequency features occurring at the same time can contribute to a SACZ episode.

4. INTRASEASONAL OSCILLATION AND SACZ: TELECONNECTION THROUGH THE TROPICAL BELT

It is well known that the MJO is an important feature of the tropical atmosphere in the 30–60 days band over the Indian and Pacific Oceans (Madden and Julian, 1972; Knutson and Weickmann, 1987; Madden and Julian, 1994; among others). EOF analysis of the OLR in the tropical region often yields two modes that explain the majority of variance and are related to the MJO activity (Knutson and Weickmann, 1987; Ferranti *et al.*,

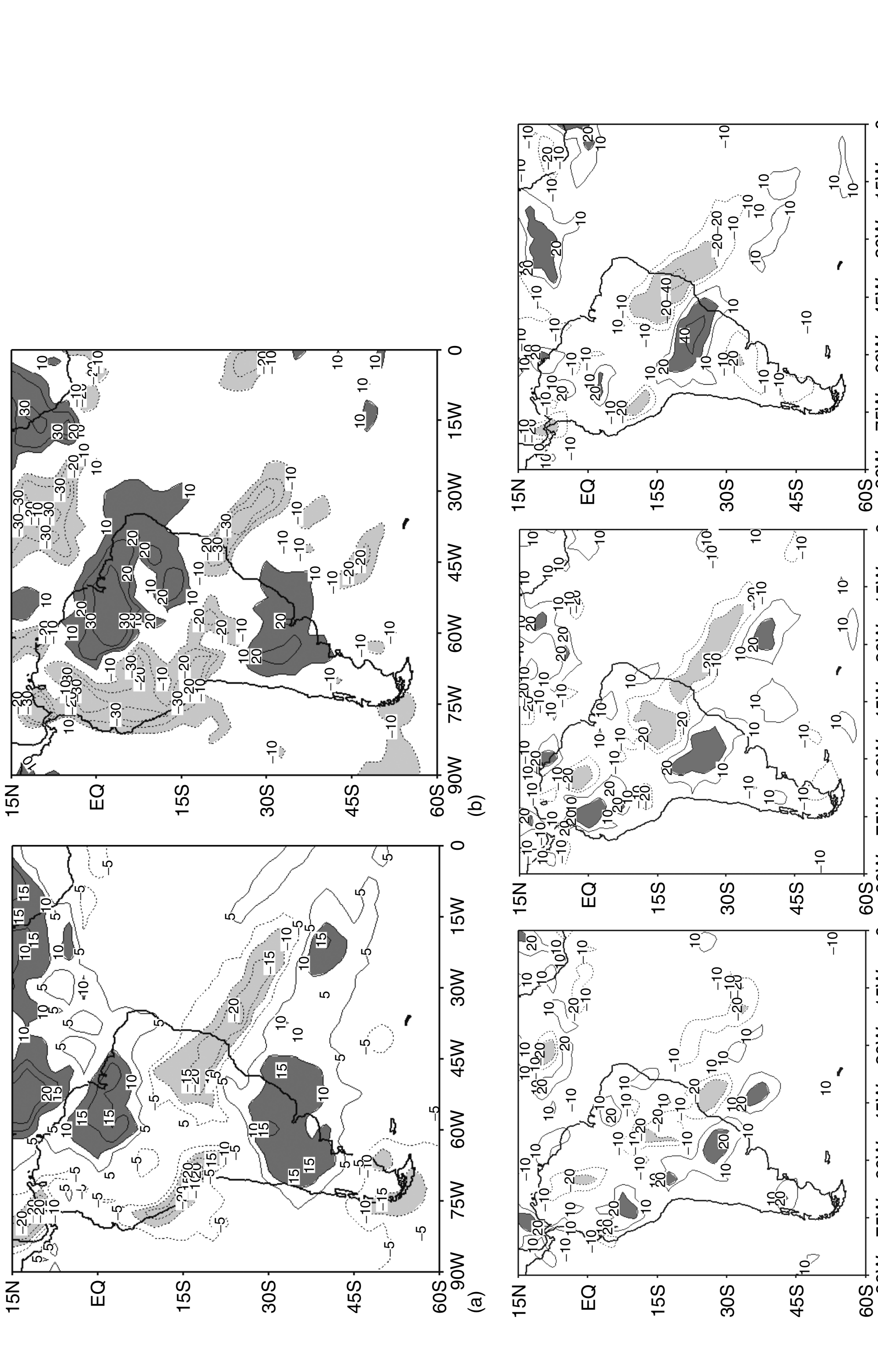

Figure 3. Comparison between intraseasonal (30–90 days) and high frequency (2–10 days) during an SACZ episode (November 22nd to 26th, 1984). (a) Average of OLR anomalies filtered in the 30–90 days; (b) average of OLR anomalies without filtering; (c) OLR anomaly pattern on 11/23/1984, filtered in the 2–10 days band; (d) OLR anomaly pattern on 11/24/1984, filtered in the 2–10 days band; (e) OLR anomaly pattern on 11/25/1984, filtered in the 2–10 days band

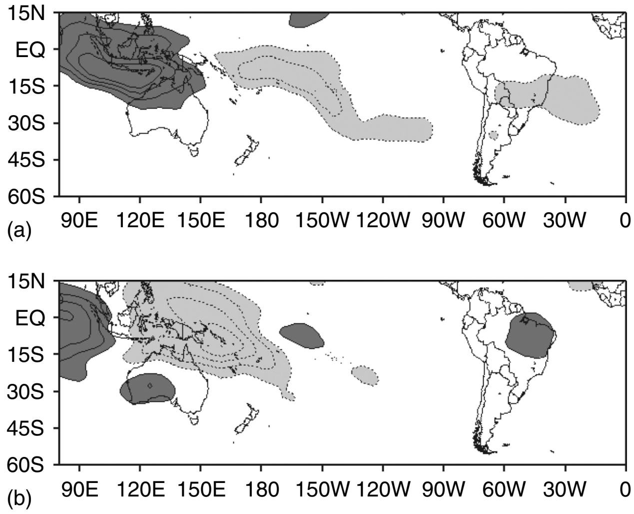

Figure 4. (a) First EOF loading of intraseasonal OLR accounting for 27.2% of summer variance; (b) second EOF loading of intraseasonal OLR accounting for 16.7% of the variance. Light shaded area are negative loadings greater than -2 W^2.m^{-4} and dark shaded area are positive values greater than 2 W^2.m^{-4}. Contour interval is 2 W^2.m^{-4}

1990; Kayano and Kousky, 1992). Those two modes can be viewed – as an illustrative point of view – as two steps of the eastward progression of the MJO along the tropical belt. In the present study, the EOF patterns are shown to describe the influence of the Indonesian convection on the SACZ convection.

The first two OLR intraseasonal loadings patterns explain 44% of the total variance and represent distinct phases of the MJO (Figure 4). This is an expected result because the data were filtered to retain intraseasonal oscillations. Similar patterns were shown in Ferranti *et al.* (1990), although they did not discuss the configurations over South America. The intention here is to explore the influence of these patterns on convection associated with SACZ. We can notice in Figure 4 that the position of the east–west dipole, associated with the MJO, is related to different areas of convection anomalies over South America. In the first EOF pattern, an area over central South America extending to the western Atlantic Ocean has the same sign as the area over central equatorial Pacific, which also seems connected with the SPCZ. Previous analyses of Casarin and Kousky (1986) and Grimm and Silva Dias (1995) have shown relations between convection in these two convergence zones. The second EOF shows a different phase of the east–west MJO dipole, and opposite signs between Indonesia and northeast Brazil. Therefore, the position and phase of the MJO in the Indian Ocean/Indonesia/West Pacific seems to be connected with convection in different regions of South America. The EOF1 pattern can be related to studies of Nogues-Paegle *et al.* (2000) and Kiladis and Weickmann (1992), and EOF2 pattern to studies of Weickmann *et al.* (1985), Knutson and Weickmann (1987) and Kayano and Kousky (1992). In Kiladis and Weickmann (1992), it is possible to see relations between convection in Indonesia and circulation features over South America through a wavetrain linking both regions in a PSA pattern. However, they do not discuss the impact of PSA on SACZ in the intraseasonal frequency band.

It is appropriate to mention that caution must be exercised in interpreting the results of the EOF analysis (Dommenget and Latif, 2002). The patterns derived from EOF analysis might be associated with very little physics due to constraints inherent in those statistical tools. Hence, the combination of more than one method is a more complete and secure methodology to apply to substantiate physical reasons behind the statistical results. Following this consideration and intending to explore the influence that the propagation of the MJO could have on the convection activity over South America, we computed crossed lagged correlations using key areas.

The sequence displayed in Figure 5(a) to (e) was obtained correlating OLR averaged over the INDO area (the box drawn in Figure 5) and the OLR values at all gridpoints. It represents an eastward migration of the convective area from the INDO region up to 120 °W, typical of an MJO displacement. The first and second

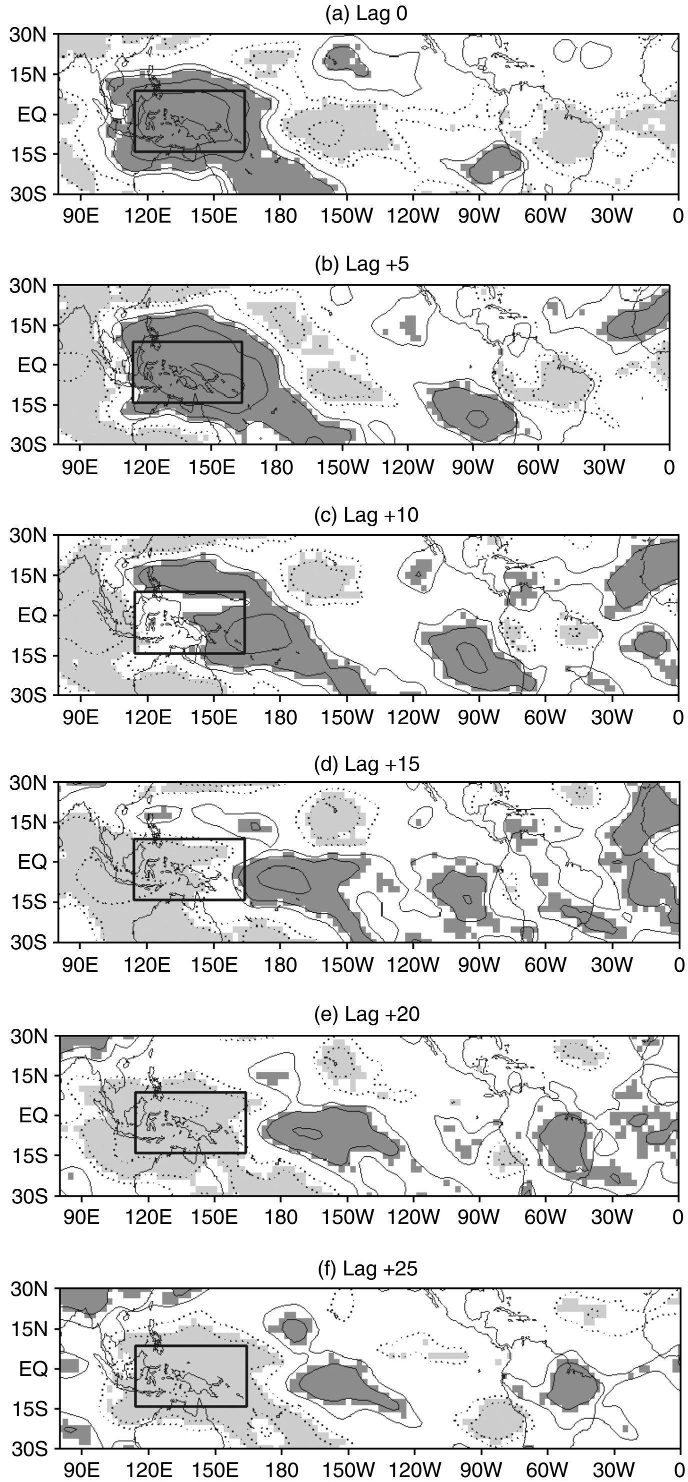

Figure 5. Lagged correlations between INDO area averaged OLR and OLR in grid points of the tropical belt. (a) Lag 0 means simultaneous correlation; (b) area averaged INDO OLR time series leads OLR in the grid points by 5 days; (c) same as (b), by 10 days; (d) same as (b), by 15 days; (e) same as (b), by 20 days; (f) same as (b), by 25 days. Areas where positive (negative) values are statistically significant at the 95% level are shaded dark (light). Contours are −0.4, −0.2, −0.1 0.1, 0.2, 0.4, 0.6

stages at lag 0 and lag 5 (Figure 5(a) and (b)), when the large core of positive values is positioned over INDO area, resemble the second loading, granting reliability to the EOF loadings. At the same time, there is an area of negative values of correlation over northeastern South America, reinforcing the feature of opposite relationship between convection in Indonesia (INDO) and northeast Brazil.

Other studies have already shown opposite behaviours between convection associated with MJO in the Indian Ocean, Indonesia and West Pacific, and convection over South America. Knutson and Weickmann (1987) used another kind of filtering to study the life cycle of MJO and they mention very briefly the influence over South America. They showed the propagation eastward of OLR and upper level divergence, and mention that the OLR signal disappears over the East Pacific. They showed that the convection near the date line decreases as new anomalies appear to the east over South America and Africa. They also mention that the Indian Ocean region experiences a renewal of convective activity accompanied by convective anomalies over South America and Africa.

The OLR pattern found by Mo and Paegle (2001) and related to PSA2 is quite similar to the relationship stated here. Their results show that convection may be suppressed over an area comprising extreme East Indian Ocean, Indonesia and extreme West Pacific (rather similar to INDO area) and at the same time would be enhanced convection over the whole northeast region of South America. This corresponds pretty much to Figure 4(b), which also shows this kind of association. More recently, Carvalho *et al*. (2004) also found a relation between the intraseasonal convective activity of the MJO and OLR in tropical South America. They found that when suppressed convection remains over Indonesia, there is an influence on the persistence of an SACZ event and the occurrence of extreme precipitation over Brazil.

Twenty-five days after convection was positioned over INDO area (see Figure 5(a)), the main tropical convective areas (Indonesia, central Pacific and northeastern South America) assume an opposite convective behaviour, as indicated by the changes in correlations signal (Figure 5(f)). The sequence in Figure 5 shows that the OLR anomalous cluster propagates eastward up to approximately 150 °W, then disappears over the East Pacific and reappears over South America. This unsmooth propagation of the convection along the tropical belt has been stated as a characteristic of the MJO. Knutson and Weickmann (1987) demonstrated that although there is no convection in the eastern equatorial Pacific, there are dynamic conditions for convection, i.e. upper level divergence, as can be seen by continuous propagation of the velocity potential field around the globe. Very recently, Hsu and Lee (2005) complemented this finding, proposing a physical mechanism to explain the jump of convection over the eastern Pacific. They proposed that an equatorial Kelvin wave, forced by deep convection in the western Pacific, would be able to propagate through the drier and cooler eastern Pacific and trigger convection in tropical South America.

There is an indication, in the sequence presented in Figure 5, that as the convectively active phase of the MJO displaces eastward over the Tropical Pacific, it stimulates convection in the SPCZ. Mathews *et al*. (1996) proposed a mechanism to explain the interaction between convection associated with MJO and convection in the SPCZ. According to them, large-scale convection can advect high potential vorticity air equatorward due to the maintenance of anticyclone in the subtropical upper atmosphere. If the MJO-related convection is positioned in the vicinity of Indonesia, this advection could induce ascent of air parcels in the SPCZ area. Approximately 10–15 days after the first stage, when convection associated with MJO is positioned in the vicinity of the International Date Line (Figure 5(d)), convection also begins in the southernmost area of SACZ. Grimm and Silva Dias (1995), using influence functions, demonstrated that convective activity over the SPCZ is able to stimulate convection over SACZ a few days after the beginning of a convective episode in the former region. The dynamic mechanism is the generation of a rotational forcing over the SACZ area, through the anomalous divergence at upper levels created by anomalous convection in the SPCZ. Apparently, the intraseasonal convective signal begins over the ocean near the SACZ position (Figure 5(c)). Carvalho *et al*. (2004) discuss the formation of SACZ over the ocean and the role of the PSA pattern. This relation between the tropics and extratropics is analysed in the next section.

Table I shows that the strength of opposite relationship between convection in INDO area and South America depends on the positioning of convection over South America. Correlating the averaged OLR emission in the three SACZ areas with OLR in the INDO area, we can see that the relation weakens as the area in South America is positioned southward (Table I). The highest magnitude of correlation between

Table I. Pearson correlation coefficients among the area averaged values of anomalous OLR filtered in the 30–90 days band. Values above (below) 0.2 (−0.2) are statistically significant at 95% level. Frames in the table evidence those values

	INDO	SACZ1	SACZ2	SACZ3
INDO	1.000	–	–	–
SACZ1	−0.212	1.000	–	–
SACZ2	−0.166	0.498	1.000	–
SACZ3	−0.107	0.030	0.741	1.000

the three SACZ areas and the INDO area occurs when the area considered is the SACZ1 (−0.212). This negative value indicates an opposite linear relation between convective events in SACZ1 and INDO areas. This result suggests that the eastward progression of MJO would affect preferably the SACZ events that occur closer to equatorial regions of Brazil. The linear relation appears to be weak as indicated by the low values of correlation. Thus, it is likely that not every SACZ event displaced to the north is influenced by the MJO.

To explore further the relation between convective events in Indonesia, associated with MJO, and convective episodes occurring in the SACZ1 area, we studied the tropical OLR field for only extreme convective events in the SACZ1 following the criterion mentioned in Section 2. According to that, 53 events were found. Therefore, on an average, 3 events occur each summer season. SACZ1 area was chosen due to the higher correlation with the INDO area and to enhance the direct influence of MJO, because this area comprises an equatorward-displaced SACZ.

To create sequential maps, we simply composite the OLR field for the previous days, preserving the duration of each event. The results of this analysis show opposite signs of anomalous convective activity between South America and areas close to Indonesia, and a dipole of convection between northeast/southeast and southern Brazil at Lags 0 and −20 (Figure 6). The typical east–west dipole associated with the MJO appears at Lag −10, when the convection is displaced eastward over the Pacific. It can be seen that a strong convective event in SACZ1 (Figure 6(c)) tends to be preceded by a convective event in the vicinity of Indonesia, which propagates eastward. It is seen that the area with opposite sign to the SACZ1 convection signal extends beyond the limits of the INDO area, comprising just part of the Maritime Continent and located mainly over the West Pacific (Figure 6(a) and (c)). The precursor convection in this region occurs around 20 days before the event takes place over South America. The dipole pattern over South America is in agreement with the results obtained in the regional EOF analysis (Section 3) and with other studies (e.g. Nogues-Paegle and Mo, 1997).

5. INTRASEASONAL OSCILLATION AND SACZ: TELECONNECTION THROUGH SUBTROPICAL FLOW

Previous studies have established a link between MJO stages and PSA modes. Mo and Higgins (1998) demonstrated that during the austral winter, convection in the extreme West Pacific, to the west of date line, is associated with PSA1, and when MJO convection is displaced eastward, blended with the SPCZ convection, the associated mode is the PSA2. More recently, Nogues-Paegle *et al*. (2000) demonstrated a similar association during the austral summer.

In the current study, we are interested in teleconnection patterns associated with SACZ convection. Thus, we have computed cross correlations between VWND at grid points and OLR in the SACZ areas to identify wave patterns associated with convection over SACZ. It is useful to keep in mind that in the case of correlation with VWND, the linear relation is such that if we consider enhanced (suppressed) convection, i.e. negative (positive) values of anomalous OLR in the SACZ, positive (negative) values of correlation would correspond to southward (northward) meridional wind, as indicated by the arrows in Figure 8. The analyses were performed for the three areas (SACZ1, 2 and 3). Considering SACZ1, the strongest pattern was found over the

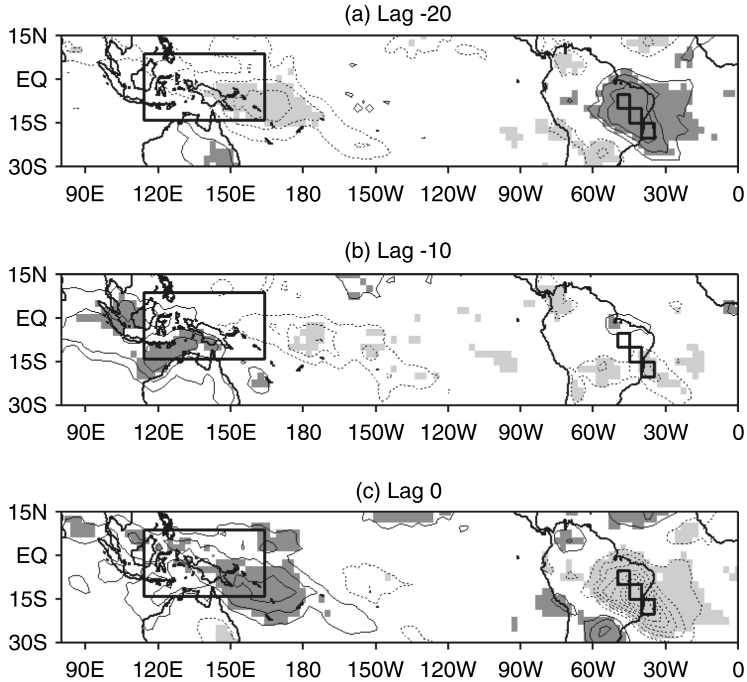

Figure 6. Sequence of composites of extreme convective events in SACZ1. (a) Average of composites 20 days before an intense event in SACZ1; (b) same as (a) but for 10 days; (c) mean convective pattern during an intense convective event in SACZ1; the figures also show the INDO area box. Areas where positive (negative) values are statistically significant at the 95% level are shaded dark (light). Contour interval is 2 W.m^{-2}

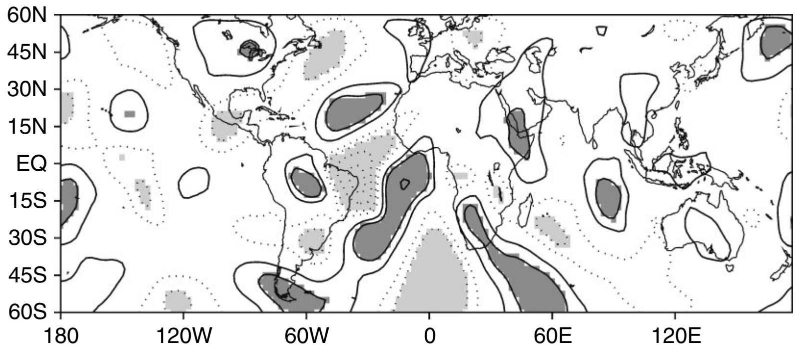

Figure 7. Correlation pattern at lag 0 between OLR averaged over SACZ1 area and VWND in the gridpoints. Contours are −0.6, −0.4, −0.2, −0.1 0.1, 0.2, 0.4. Areas where positive (negative) values are statistically significant at the 95% level are shaded dark (light)

Atlantic and Indian Ocean, showing a wavetrain from extreme northeastern Brazil towards higher latitudes of South Atlantic Ocean, south of Africa and then turning equatorward into the tropical Indian Ocean (Figure 7). This pattern has not been identified in previous studies. One possible explanation to this configuration might be that convection in this region would force an anomalous atmospheric circulation pattern that could excite Rossby waves over the extratropical South Atlantic and Indian Ocean. As the final centre of this pattern is over the Indian Ocean, it could be associated with a new pulse of the MJO. Circulation features are also evident over the North Atlantic close to Central and North America, which is consistent with previous studies that relate the Pacific North America pattern with precipitation over northeast Brazil (Nobre and Shukla, 1996).

The cross correlations between OLR and VWND in SACZ2 and SACZ3 show similar patterns of a PSA wave pattern over Pacific and South America. Therefore, as the correlations are higher considering SACZ3, we discuss the results for this area. The correlations were performed with lags to explore the time evolution of features. The sequence in Figure 8 indicates how MJO, the wave flow in the subtropical latitudes and convection in the SACZ could be linked. Twenty-five days before convection in the SACZ is established, there are opposite conditions in this area and enhanced convection in the extreme East Indian Ocean. Furthermore, the convective activity tends to be suppressed over the central Pacific. There is also a slight indication that convection begins to the southwest of SACZ3 region (Figure 8(a)). The upper wave flow associated with this convective scenario shows a Rossby wavetrain extending from Australia to South America. This PSA-like wave train maintains an anomalous ridge to the southwest of the SACZ3 (Figure 8(b)).

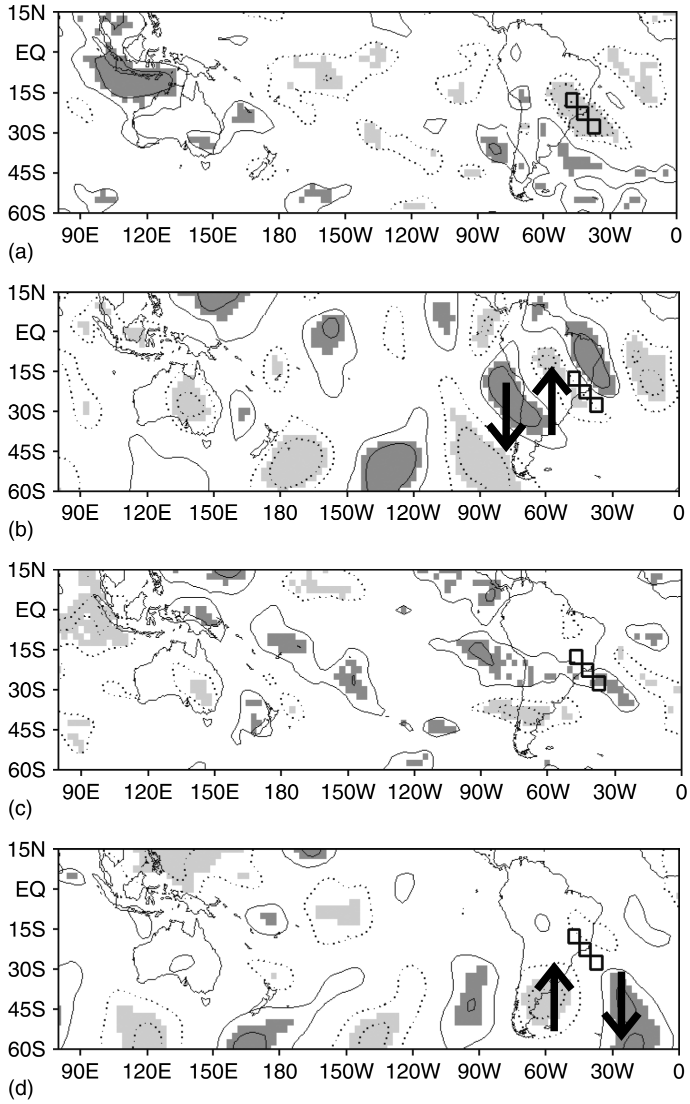

Figure 8. (a) Correlation pattern at lag −25 between OLR averaged over SACZ3 area and OLR in the gridpoints; (b) correlation pattern at lag −25 between OLR averaged over SACZ3 area and VWND in the gridpoints; (c) same as (a) but for lag −10; (d) same as (b) but for lag −10; (e) same as (a) but for lag 0; (f) same as (b) but for lag 0. Areas where positive (negative) values are statistically significant at the 95% level are shaded dark (light). Contours are −0.2, −0.1 0.1, 0.2

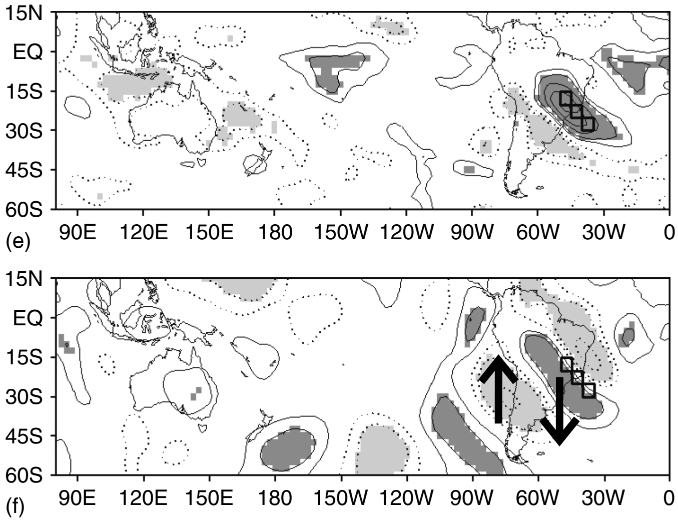

Figure 8. (*Continued*)

At lag −10, the East Indian Ocean shows suppressed convection, the SPCZ region is active, and convection develops over the ocean areas of the SACZ region (Figure 8(c)). This convection can be associated with a mid-latitude trough over southern Atlantic to the southeast of South America and is part of a wavetrain in midlatitudes. This wave train is mostly confined to latitudes south of 45 °S but tilts equatorward at 150 °W (Figure 8(d)). Carvalho *et al.* (2004) have classified SACZ episodes according to geographical position and intensity. They found a distinct category of episodes where the main convective activity occurs displaced eastward to the Atlantic, which they named *oceanic SACZ*. According to their analysis, such events are more likely to be influenced by mid-latitude wavetrains coming from the South Pacific and bending northeastward to the east of the Andes. Hence, our results are consistent with theirs.

Figure 8(e) and (f) shows the patterns of simultaneous correlation (LAG 0) of convection in the SACZ3 with OLR and VWND, respectively. The general conditions are pretty much the opposite of those in lag −25. There is suppressed convective activity in southern Indonesia and also to the southwest of the SACZ3 area. Conversely, convection is active in the SACZ and over the central tropical Pacific, at approximately 150 °W (Figure 8(e)). Such a dipole of suppressed/enhanced convection over Indonesia/central Pacific inferred from the areas of significant correlations, even though not extensive, is recognized as part of the MJO life cycle and has been related to the PSA2 (Nogues-Paegle *et al*., 2000). The correlation pattern with VWND (Figure 8(f)) indicates the presence of an anomalous cyclonic circulation southwest of the SACZ3; a well-known feature related to enhanced convection associated with this occurrence (Casarin and Kousky, 1986; Liebmann *et al*., 1999). This trough is part of a noticeable wave train along a great circular route that extends from the vicinity of Indonesia/Australia to the SACZ in South America. This wave train is able to maintain a trough (or a ridge) over South America, affecting the SACZ3 formation or maintenance as discussed in previous studies.

Composites of low-frequency OLR and anomalous wind field at 200 hPa, considering extreme events in SACZ1, SACZ2 and SACZ3, display similar features of a PSA pattern connecting the tropical West Pacific/Indonesia to SACZ convection (Figure 9). However, some differences can be noticed. In Figure 9(b) and (c), which represent SACZ2 and SACZ3, the anomalous positive OLR in the Indonesian region is located to the west of the case of SACZ1 (Figure 9(a)). Comparing these fields with Figure 4(a), and (b), cases of SACZ2 and SACZ3 represent the EOF1, where connection of MJO with SACZ can exist via SPCZ and PSA; whereas cases of SACZ1 represent the EOF2, where the tropical South America convection can be influenced by eastern displacement of MJO signal, also discussed in Figure 6. Besides, in Figure 9, the PSA pattern is more organized in the cases of SACZ2 and SACZ3 than in the case of SACZ1, consistent with the cross correlation analysis between meridional wind and OLR in Figure 7. Consistent also, is the anomalous

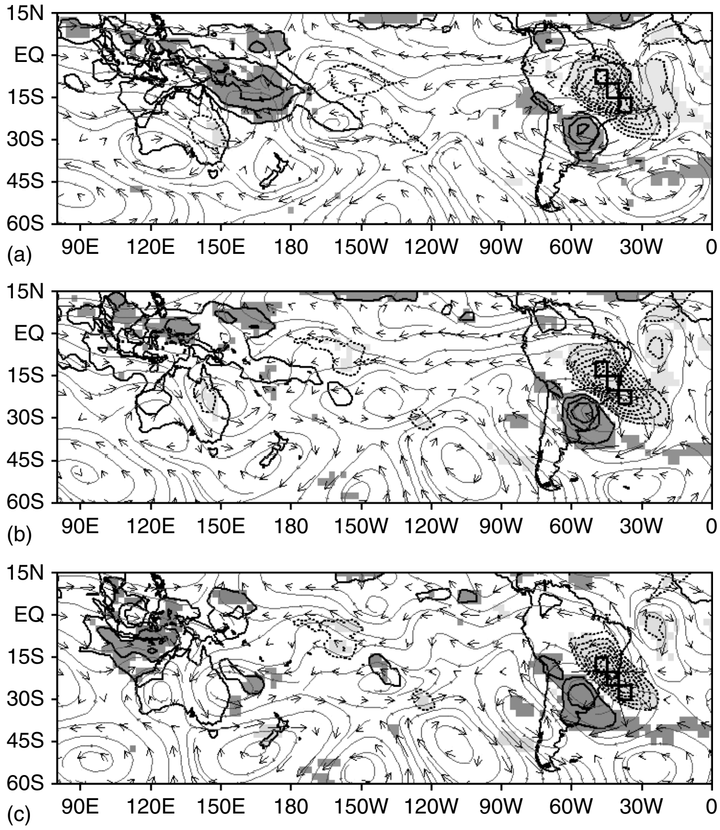

Figure 9. Composite of extreme convective events in (a) SACZ1, (b) SACZ2 and (c) SACZ3 regions. Areas where positive (negative) values of OLR anomalies are statistically significant at the 95% level are shaded dark (light). The wind vectors and streamlines are not masked by statistical significance. OLR contour interval is 2 W.m^{-2}

anticyclonic circulation noticed over southwest South Atlantic Ocean, which was more intense in the case of SACZ1 than in the other two cases.

6. SUMMARY AND FINAL DISCUSSION

This study summarized and complemented the current knowledge about the intraseasonal variability affecting the SACZ and the associated teleconnections. We discussed aspects of low and high-frequency variability associated with convection in the SACZ and the role of convection over and near Indonesia. The teleconnections were identified using EOF and cross correlation analyses considering areas of strong convection over Indonesia and SACZ region. Composites of extreme SACZ episodes confirm the general characteristics observed in the other methods, and enhance differences between SACZ1 and SACZ2/SACZ3.

Dominant features of high frequency over South America were related to frontal systems and showed similarities with the intraseasonal variability patterns over the continent. Intraseasonal variability modes of convection in Indonesia and SACZ regions were analysed and features of the tropical–extratropical interactions were discussed on the basis of dominant atmospheric patterns. The discussion was focused on two aspects. Firstly, convection in the Indonesian region, which was supposed as being part of the MJO cycle and affecting tropical South America. Secondly, teleconnections linking the PSA pattern to convection in the SACZ. The results obtained in this study confirm assertions of previous studies and indicate that part of the intraseasonal variability in the SACZ convection may be related to two main mechanisms.

The first one would be the equatorial eastward progression of the MJO envelope of convection/upper divergence. Kousky and Kayano (1994), Kiladis and Weickmann (1992), Knutson and Weickmann (1987) and Weickmann. *et al*. (1985) have already suggested the association between the eastward displacement of the MJO signal and convection over tropical portions of Brazil. We call this mechanism *tropical zonal mode*, just as a matter of identification. This mode features a 'see-saw' pattern of convection between Indonesia and the tropical portion of South America (represented in this study by the SACZ1 region). At the same time, there is a remarkable west–east OLR dipole between the Indonesian region and central-west tropical Pacific. Other studies have already shown this configuration associated with the MJO, but without a discussion of the influence on the SACZ.

The second would be through a PSA-like wavetrain in the intraseasonal scale over the Pacific, shown previously by Nogues-Paegle *et al*. (2000) and referred to here as the *tropical/extratropical mode*. This mode was identified by the presence of PSA-like dominant patterns associated with convection in the SACZ areas. The influence of this mode on South America convection was also discussed in previous studies by Carvalho *et al*. (2004), Nogues-Paegle *et al*. (2000), Mo and Paegle (2001).

As we could expect, the intraseasonal variability in the SACZ is not isolated but connected to other frequencies of variability, specially the high-frequency band. The high-frequency systems (frontal systems) sweeping over South America in the presence of the tropical/extratropical mode could trigger a SACZ episode. The influence of frontal systems in the triggering and maintenance of a SACZ event has been discussed in Siqueira and Machado (2003). Nevertheless, the day-to-day observations also show that not every frontal system results in a SACZ episode, therefore demanding an adequate phasing between the low and high frequencies to create conditions for more permanent SACZ convective episodes. The suggested mechanism is such that, under the influence of a distinguished PSA episode, the frontal system that moves northward over the continent could trigger a SACZ episode. The occurrence of convection in the SACZ2 or SACZ3 areas could be dependent on the position of the trough belonging to the PSA pattern. The occurrence of convection in SACZ1 (displaced northward) is also influenced by the tropical zonal mode MJO. The convection in this northernmost position triggers a wavetrain towards the South Atlantic and the Indian Ocean, a feature that deserves further analysis.

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