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Active and Break Phases in the South American Monsoon System

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ABSTRACT

The South American monsoon system (SAMS) refers to the austral summer season features of deep convective activity and large-scale circulation. This study examines intraseasonal variations in the low-level wind circulation in the Amazon and their modulating effects on active and ‘‘break’’ phases in SAMS. Daily averages of outgoing longwave radiation (OLR), NCEP–NCAR reanalysis, and gridded rainfall station data in Brazil are used from 1 November to 28 February 1980–99. The direction of wind anomalies (10–70 days) in the Rondônia State, Brazil, is used to classify periods of westerly (W) and easterly (E) low-level wind regimes. Composites of W regime show low-level wind anomalies crossing the equator southward and closing in a cyclonic anomalous circulation off the coast of Argentina and Uruguay. Broad areas of enhanced convection and rainfall are observed in central and southeast Brazil. Suppressed convection is observed over the Bolivian Altiplano and in northern South America. In contrast, in the E regime, opposite patterns are observed in the low-level circulation, convection, and rainfall anomalies. The duration of active (W regimes) and break (E regimes) periods are quite similar, with median values of 4 and 5 days, respectively. Further investigation showed that the region of convection and rainfall anomalies over Venezuela and northwest Brazil is observed only in the 10–30-day band. Comparison of the results shown here with previous studies indicates the importance of intraseasonal variations in the activity of SAMS.

1. Introduction

The intense convective activity and heavy precipitation begins in northwestern South America in late August and marches progressively southeastward until it reaches the Brazilian highland. The wet season peaks in the core of the Amazon in austral summer (December–February). Deep convection begins to weaken over the Amazon in early March and the dry season persists throughout most of the austral winter (Horel et al. 1989; Jones 1990). It has been increasingly common to refer to this strong summertime convective activity, intense precipitation, and large-scale atmospheric circulation features as the South American monsoon system (SAMS). In fact, the study of Zhou and Lau (1998) reviewed the early definitions of monsoon systems, originally formulated to account for reversals in the large-scale circulation that are driven by differential heating between land masses and oceans. The Zhou and Lau (1998) results, which were based on monthly averaged data, indeed demonstrated that the summer season in South America contains the main ingredients to be characterized as a monsoon system. Of particular importance is their observation that easterly winds prevail in the tropical Atlantic and in eastern South America throughout the entire year and seasonal reversal of surface winds is not immediately apparent. However, when the annual mean is removed from summer (January) and winter (July) composites of surface winds, the characteristic reversal in anomalous low-level circulation becomes evident (see Zhou and Lau 1998, their Fig. 9). In the context of monsoon systems, an important characteristic observed in the Asian–Australian region relates to the frequent and persistent active and inactive (or ‘‘break’’) periods in the intensity of rainfall amounts. In this respect, tropical intraseasonal oscillations have been found to strongly modulate these active and break periods of the Asian–Australian monsoon system (Vernekar et al. 1993). Thus, the Madden–Julian oscillation (MJO; Madden and Julian 1994) is key in the occurrence of active and break phases of the Asian–Australian monsoon.

The behavior of active and break phases in SAMS has not been extensively addressed in previous studies. Some limited observational evidence of variations in the structure of convection and different large-scale cir-

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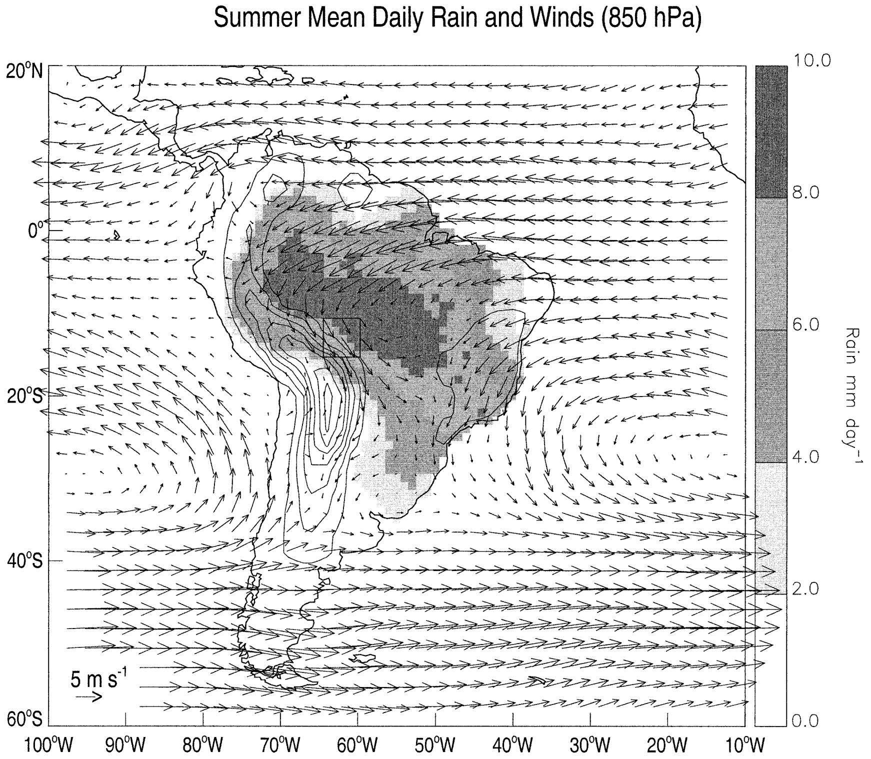

FIG. 1. Mean daily rainfall (shading; mm day^{-1}) and low-level (850 hPa) winds (m s^{-1}) (arrows) during austral summer (1 Nov–28 Feb 1980–99). Thin solid lines indicate the terrain elevation (first contour equal to 500 m, and 500-m intervals). The box indicated by thin lines in Rondônia State, Brazil, is used as the reference region in the composites. Rainfall is available from stations in Brazil; values outside Brazilian territory are extrapolated.

culation regimes has been gathered in the recent Large-Scale Biosphere Atmosphere (LBA) experiment of the intensive field campaign in January–March 1999. This experiment, which was part of the Wet Season Atmospheric Mesoscale Campaign (WETAMC) and LBA Tropical Rainfall Measuring Mission (TRMM) validation experiment, took place in the Brazilian state of Rondônia over the southwest part of the Amazon (Silva Dias et al. 2000). Periods of easterly and westerly 850-hPa winds in several sites in Rondônia seemed to be associated with different physical and structural characteristics of mesoscale convective systems (Cifelli et al. 2002; Petersen et al. 2001; Carvalho et al. 2002). The objective of this note is to present long-term statistical analysis to show further observational evidence that easterly and westerly wind anomalies associated with intraseasonal variations are significantly linked to changes in large-scale convective activity and precipitation in SAMS.

2. Datasets

Austral summer seasons from 1 November to 28 February for the period 1980–99 (19 seasons) are used. Daily averages of outgoing longwave radiation (OLR) are used to characterize large-scale aspects of tropical convection (Liebmann and Smith 1996). Daily low-level and upper-level zonal (U850, U200) and meridional (V850, V200) components of the wind and geopotential height (H200) from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) are used to characterize the large-scale circulation. Active and break phases in SAMS are further assessed with daily rainfall amounts from station data in Brazil [Agência Nacional de Energia Elétrica (ANEEL)]. Daily ANEEL rainfall data were gridded by the NCEP Climate Prediction Center (CPC) in 1° latitude–longitude resolution arrays using a Cressman (1959) scheme with modifications (Glahn et al. 1985; Charba et al. 1992). Seventeen austral summer seasons (1 November–28 February) for the period 1980–97 are used.

3. South America Monsoon System (SAMS)

A number of studies have provided insight in the time-averaged dynamics associated with the region of convective activity in South America (Silva Dias et al. 1983; Gandu and Geisler 1991; Gandu and Silva Dias 1998; Figueroa et al. 1995). To put this in context, Fig. 1 shows the average daily rainfall observed during summertime (1 November–28 February). A broad region

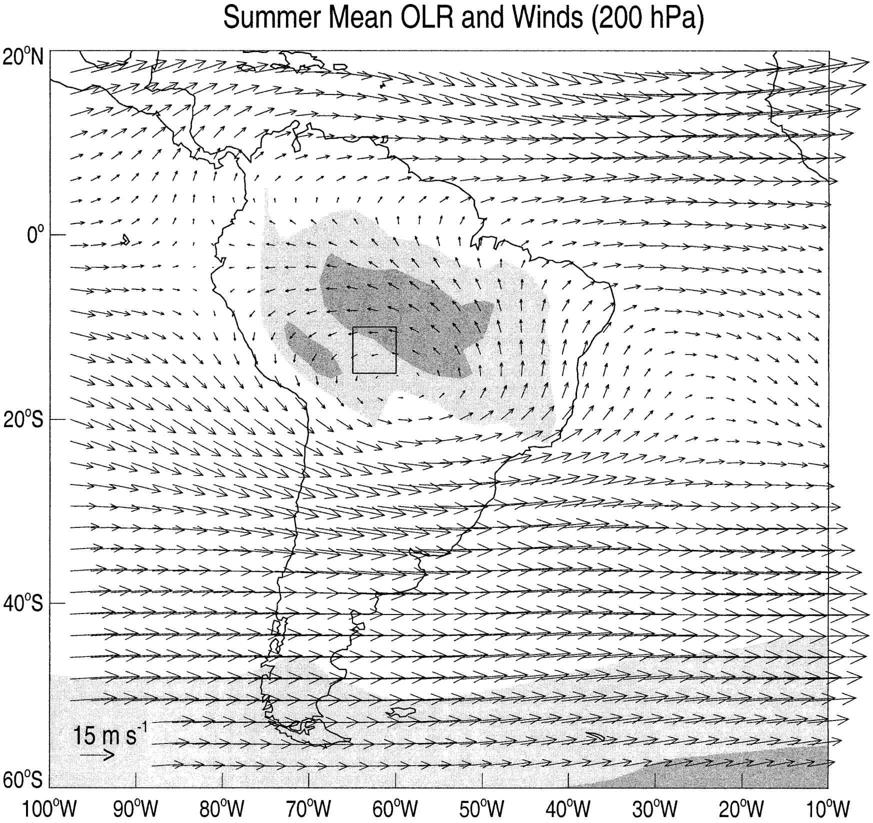

FIG. 2. Mean OLR (shading) and upper-level (200 hPa) winds (m s^{-1}) (arrows) during austral summer (1 Nov–28 Feb 1980–99). Light (heavy) shadings denote 200 $\leq$ OLR $\leq$ 220 W m^{-2} (180 $\leq$ OLR $\leq$ 200 W m^{-2}). Reference region in Rondônia, Brazil, is indicated by thin solid lines.

approximately oriented in the northwest–southeast direction with mean rainfall amounts in excess of 4 mm day^{-1} covers most of the tropical and subtropical South American continent. Note that precipitation data is available only from stations in Brazil and, therefore, rainfall values outside the Brazilian territory are extrapolated. The mean low-level (850 hPa) circulation derived from the NCEP–NCAR reanalysis shows the typical easterly winds near the equator. On the eastern slopes of the Andes Mountains (Fig. 1, thin solid lines), the topographic barrier forces the low-level circulation to veer to southeast and then run toward subtropical South America. Consistent with the region of intense precipitation, the mean summertime OLR field exhibits strong convective activity (OLR $\leq$ 200 W m^{-2}) and the characteristic upper-level (200 hPa) circulation with the Bolivian high and the downstream trough in northeast Brazil (Fig. 2; Gandu and Silva Dias 1998). The box indicated by thin solid lines in Figs. 1 and 2 is approximately collocated with the Brazilian state of Rondônia (13°–9°S, 64°–60°W), where the WETAMC TRMM–LBA experiment was realized in January–March 1999. As discussed in the introduction, observations during the WETAMC TRMM–LBA experiment suggested significant differences in the structure of mesoscale convection during periods of westerly and easterly winds. For this reason, this box is taken as the reference region for the statistical analysis that will be shown next. In addition, it is important to observe that although the mean low-level winds near the state of Rondônia are from the northwest, the variability in the wind direction is significantly high. This can be inferred by the subseasonal standard deviation in the meridional component of the wind at 850 hPa (V850) (Fig. 3, contours). The region of maximum subseasonal V850 variability is found just to the southeast of the reference region. It is worth noticing that the subseasonal OLR standard deviation is large to the east of the region of maximum mean convective activity, that is, extending from northeast Brazil toward Uruguay and northern Argentina. This region exhibits significant peaks in the OLR variance spectrum, especially at 30–60, 27, 16, 10, and 8 days (Liebmann et al. 1999).

4. Intraseasonal variations in westerly and easterly low-level winds

The basic hypothesis of this study contends that active and break phases in convective activity in SAMS are directly associated with intraseasonal variations in the

Subseasonal Standard Deviation OLR and V (850 hPa)

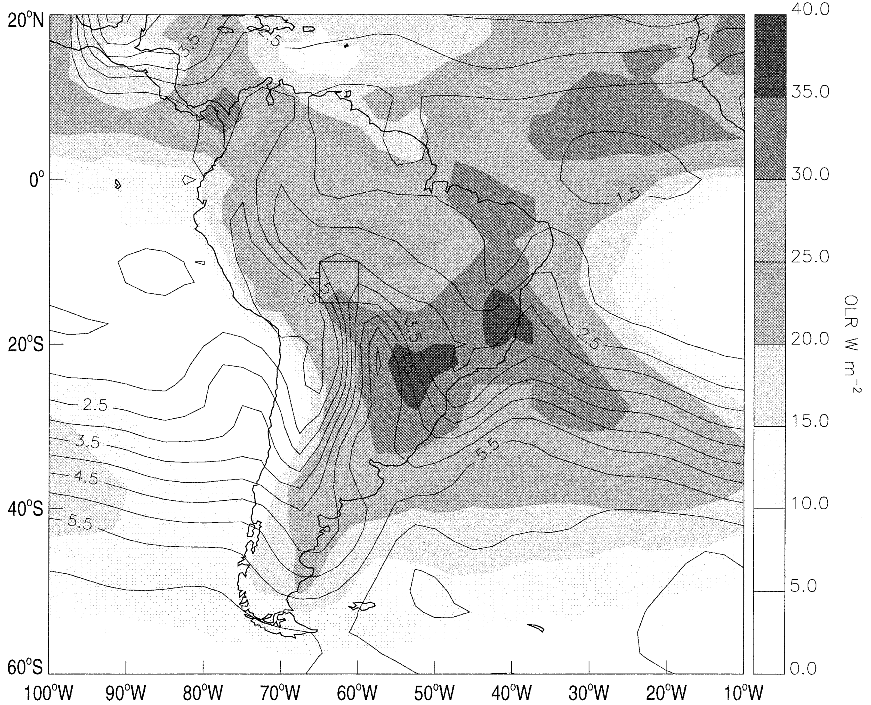

FIG. 3. Subseasonal std dev of OLR (shading; W m^{-2}) and meridional wind component at 850 hPa (V850) (contours; m s^{-1}). Contour interval is 0.5 m s^{-1}.

low-level circulation in the tropical region extending from the eastern slopes of the Andes and Amazon basin toward central and southeast Brazil. The frequency distribution of the wind direction at 850 hPa spatially averaged over the reference region during 1 November–28 February 1980–99 (hereafter NDJF) is displayed in Fig. 4. The wind direction is counted in clockwise degrees from the northern direction. Since the prevailing winds in the reference region are from the northwest quadrant, the frequency distribution has a positive skewness toward angles between 270° and 360° (median value equal to 300.3°). Nonetheless, the percentage of summer days with low-level wind direction from 45° to 180° is not negligible (18.4%) and indicates the degree of wind variability in the western Amazon region.

Rondonia (NDJF)
Wind Direction (850 hPa)

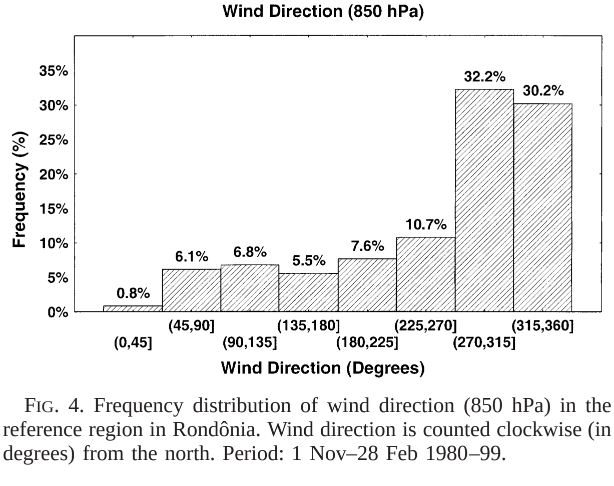

FIG. 4. Frequency distribution of wind direction (850 hPa) in the reference region in Rondônia. Wind direction is counted clockwise (in degrees) from the north. Period: 1 Nov–28 Feb 1980–99.

Carvalho et al. (2002) investigated the distribution of spectral variance of OLR and zonal wind component (U850) spatially averaged in the reference region. The spectrum of OLR variance showed several significant spectral peaks at 18.29, 9.48, 7.31, and 4.34 days. The fact that the intense large-scale convective activity over the core of the Amazon does not exhibit variations associated with the MJO as strong as the ones observed over the Indian and western Pacific Oceans has been noted in previous studies (Knutson and Weickmann 1987; Jones and Weare 1996). Likewise, the zonal wind component indicated spectral peaks of 19.69, 14.22, 9.85, 7.11, and 4.65 days that exceeded the red noise background spectrum. In order to distinguish between intraseasonal and synoptic variations, a Lanczos bandpass filter (Duchon 1979; Jones et al. 1998), with 151 weights and cutoff periods of 10 and 70 days, was applied to the time series of OLR, U850, V850, and the geopotential height at 200 hPa (H200). The next step in the analysis consisted in computing the direction (α) of the low-level wind anomaly (10–70 days) for each grid point in the domain during NDJF. The frequency distribution of the direction of the wind anomaly spatially averaged in the reference region is shown in Fig. 5. The distribution has mean and median values equal

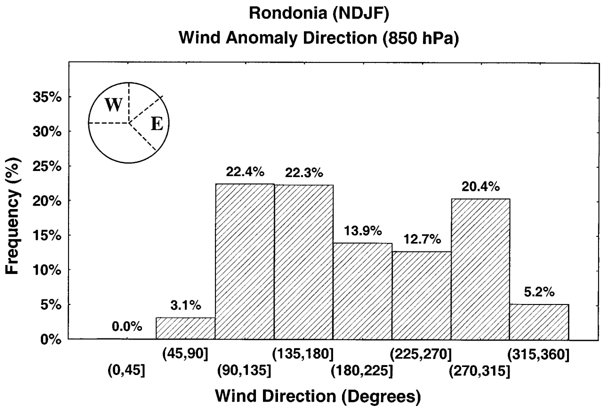

FIG. 5. Frequency distribution of α at 850 hPa in the reference region in Rondônia. Wind direction is counted clockwise (in degrees) from the north. Period: 1 Nov–28 Feb 1980–99. The inset denotes the ranges of wind anomaly direction used to compute composites: westerlies ($270° \leq \alpha < 360°$) and easterlies ($45° \leq \alpha \leq 135°$).

to 199.05° and 187.14°, respectively. It is clear from the histogram that the variability of α can occur in two quite different categories (or regimes); that is, wind anomalies with predominantly westerly or easterly components. In the following analysis, we investigate the variability in SAMS during these two distinct regimes. Two samples were extracted from the 19 austral summer seasons such that the easterly wind anomalies regime (E) is hereafter referred to periods in which $45° \leq \alpha \leq 135°$. Likewise, westerly wind anomalies regime (W) is defined when $270° \leq \alpha < 360°$ (Fig. 5). Note therefore that westerly (easterly) wind anomalies regimes are situations with wind direction similar (dissimilar) to the mean winds in the reference region. Furthermore, this definition implies in equivalent sample sizes of E and W regimes (582 days each), such that the numbers of independent events were 115 (E) and 128 (W), respectively.

5. Active and break phases in the SAMS

The samples of W and E regimes of low-level wind anomaly direction (10–70 days) were used to make composites and investigate the variability of SAMS. Figure 6 shows the composites of westerly (top) and easterly (bottom) circulation anomalies. The composites of wind vector anomalies were made by averaging the U850 and V850 anomalies on the dates of the W and E samples. Superimposed on these plots are the corresponding composites of OLR anomalies. A local t test was applied to each OLR composite to assess the statistical significance. Only OLR anomalies that were statistically significant at 95% level are shaded. In the W regime, the low-level wind anomalies cross the equator southward passing over the reference region, run toward southeast Brazil, and close in a cyclonic anomalous circulation just off the coast of Argentina and Uruguay. A broad area of negative OLR anomalies is observed to the southeast of the reference region (OLR ≤ -3 W m^{-2}), which is indicative of enhanced convective activity. Another region of negative OLR anomalies is also observed in the region of cyclonic circulation. It is interesting to note that in the Altiplano in Bolivia and in the northern part of South America, positive OLR anomalies are present in the composites. In contrast, in the E regime, opposite patterns are observed in the low-level circulation and OLR anomalies. An anticyclonic anomalous circulation is observed off the coast of Argentina and Uruguay such that the wind anomalies penetrate southeast Brazil, extend over the reference region and then cross the equator. Positive OLR anomalies greater than 3 W m^{-2} (suppressed convective activity) are located over southeast Brazil. Negative OLR anomalies suggesting enhanced convection are now observed over the Altiplano and Venezuela. The contrasting situations during W and E regimes and the patterns of OLR anomalies suggest that active and break episodes in SAMS are modulated by intraseasonal variations. While the core of the Amazon basin does not seem to be very sensitive, the eastern half of the Brazilian territory, the Altiplano and the northern part of South America show clear and robust signals. Indeed, similar patterns in low-level circulation anomalies can be found in Maloney and Hartmann (1998), who used an index of U850 anomalies (20–80 days) to composite different phases of the MJO life cycle. The composite of W (E) regimes shown in Fig. 6 is characteristic of the phase 2 (phase 6) in Maloney and Hartmann (1998, see their Figs. 4 and 10).

The importance of intraseasonal W and E regimes in modulating the SAMS activity is further corroborated with composites of daily rainfall anomalies in Brazil (Fig. 7). Rainfall anomalies were obtained by first removing the daily climatology and then applying a 5-day running mean (1 November–28 February, 1980–97). The composites were computed by averaging the U850 and V850 intraseasonal and rainfall anomalies on the dates of W and E samples (113 and 104 independent events, respectively). Only rainfall anomalies that pass the local t test of the 95% significance level are shaded. Consistent with the OLR anomaly composites, a dipole of above- and below-average rainfall is observed in central-southeast and northwestern Brazil, respectively. Important to note is that the patterns of low-level intraseasonal circulation anomalies shown in Figs. 6 and 7 exhibit close resemblance to the monthly anomalies discussed by Zhou and Lau (1998, cf. their Fig. 9). During active phases (or W regimes), westerly anomalies are observed over the core of the Amazon basin extending toward southeast Brazil and closing in the cyclonic circulation over the subtropics of South America. In contrast, the break phases (or E regimes) display easterly anomalies from southeast Brazil and crossing the equator northward, a circulation pattern, as shown by Zhou and Lau (1998), more typical of the austral winter when convective activity is observed in northwestern regions of South America.

Figure 8 shows the dispersion diagram of the duration

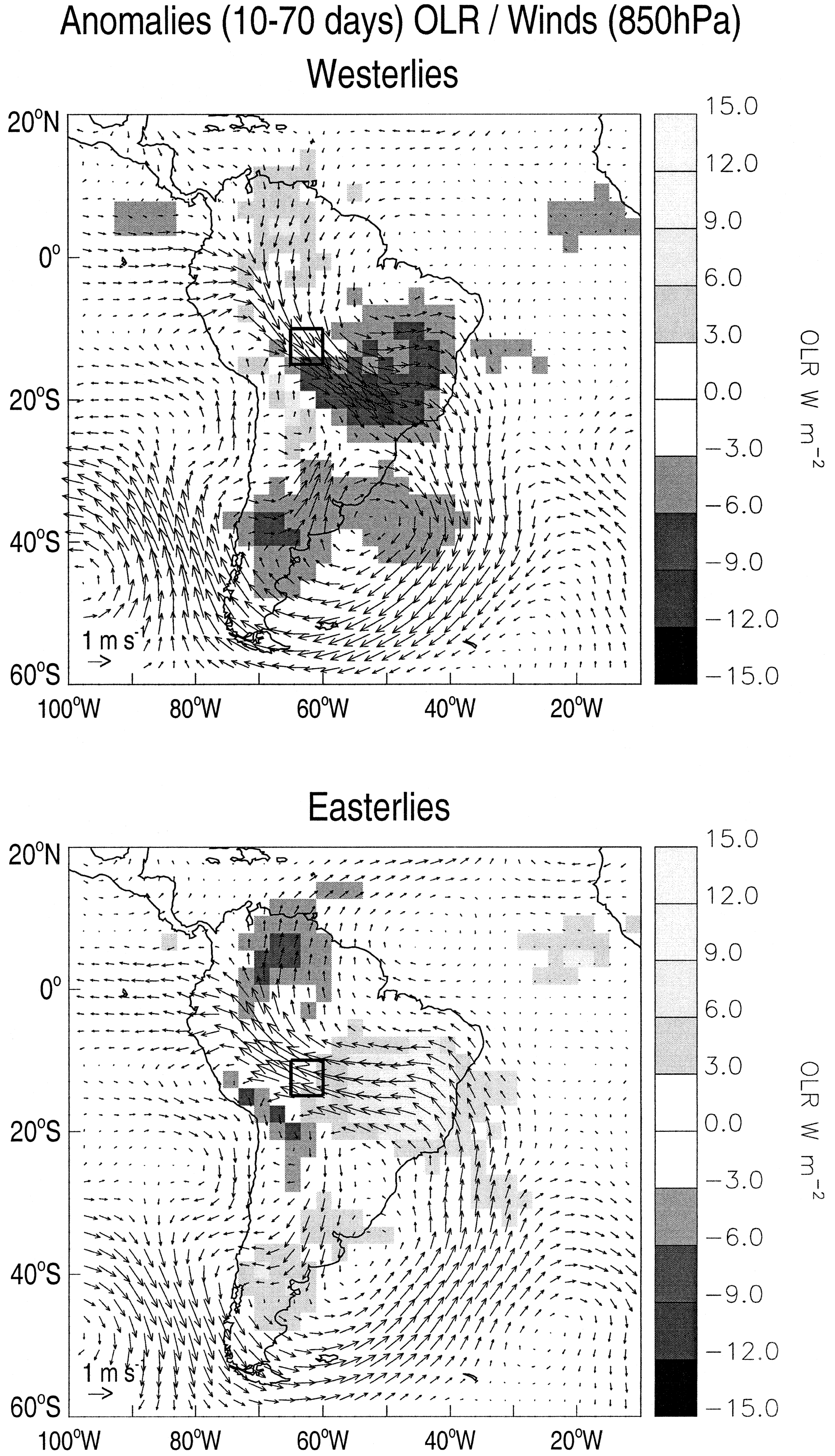

FIG. 6. Composites of OLR (shading) and wind (850-hPa) anomalies during (top) westerly and (bottom) easterly wind regimes. Anomalies refer to 10–70-day variations. Only OLR anomalies significant at 95% level are indicated.

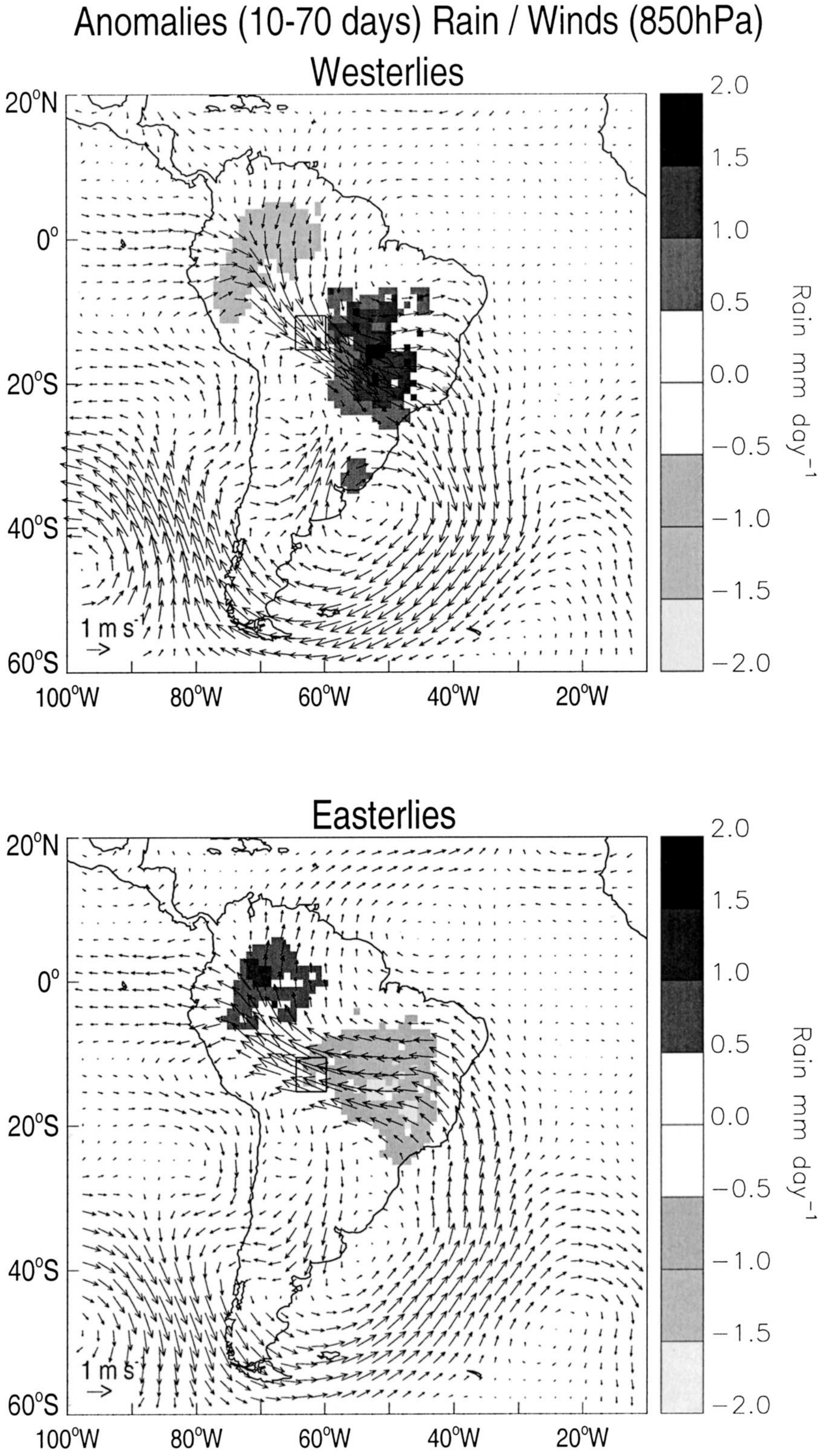

FIG. 7. Composites of rainfall (shading) and wind (850 hPa) anomalies during (top) westerly and (bottom) easterly wind regimes. Only rainfall anomalies significant at 95% level are indicated.

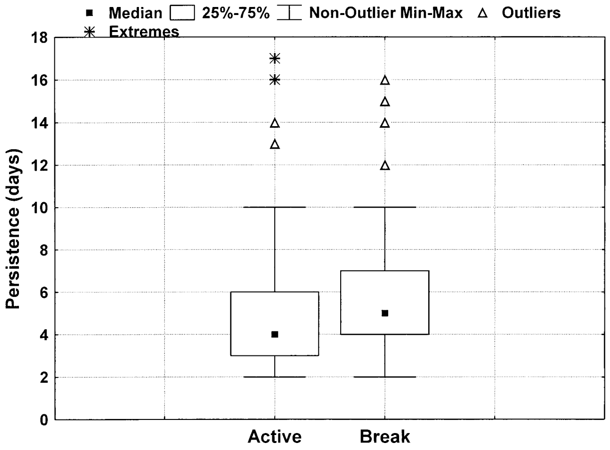

FIG. 8. Dispersion diagram of the persistence of active (W regimes) and break (E regimes) phases in SAMS.

of active (W regimes) and break (E regimes) phases in SAMS. The persistence was obtained by counting the number of consecutive days in the independent events for both regimes with the requirement of at least two consecutive days. Similar distributions are found with the exception of a slight difference in the median duration: 4 days for active phases and 5 days for break regimes. Also shown are the range of the 25 and 75 percentiles and outliers (defined as those values outside 1.5 the interquartile range). A few cases of extreme duration are observed (above 15 days).

It is relevant to note that the methodology used in this study is different from previous studies that examined the role of intraseasonal variations in South America. Typically, composite analyses are made using OLR anomalies as the reference parameter to select cases and then composite the circulation anomalies (see, e.g., Nogués-Paegle and Mo 1997; Nogués-Paegle et al. 2000). In this study, the wind anomaly direction in the Amazon region is employed as the reference parameter. Furthermore, the fact that OLR and rainfall anomalies during W and E regimes are observed with anomalous circulations extending to the midlatitudes of South America is indicative of possible teleconnections. Composites of intraseasonal anomalies of H200 (Fig. 9) were also constructed by averaging the anomalies on the dates of W and E regimes (1 November–28 February 1980–99). In both regimes, regions of positive and negative H200 anomalies, which are statistically significant at the 95% level, extend from the southeastern Pacific toward the midlatitudes of South America. The patterns of OLR and H200 anomalies bear some resemblance to the wave train patterns observed in previous studies. Intraseasonal variability with periods between 30 and 60 days modulates precipitation in the South Atlantic convergence zone (SACZ) and some studies have related this variability to Rossby wave propagation linked to MJO events in the South Pacific convergence zone (SPCZ; Nogués-Paegle and Mo 1997; Liebmann et al. 1999; Nogués-Paegle et al. 2000). We have additionally filtered the fields of OLR, U850, and V850 in bands of 10–30 and 30–70 days. Composites for each band averaged on the corresponding westerly and easterly wind direction anomalies events were constructed. The spatial signals in OLR, rainfall, and low-level wind circulation anomalies were observed in all three bands (10–30, 30–70, and 10–70 days). Whether or not the large signal of 30–60-day variability in southeastern South America is exclusively due to the MJO remains an open question. Likewise, it needs to be demonstrated how much of the 10–30-day variability is coherent with variations in the 30–60-day band and the exact role of the MJO. The sensitivity of the composites was further tested by moving the reference region from the state of Rondônia to the region of maximum V850 subseasonal variability (Fig. 3), and in general, the spatial patterns are similar. However, the region of OLR and rainfall anomalies over Venezuela and northwest Brazil (Figs. 6 and 7) is observed only in the 10–30-day band. The composite analysis was also performed in extended austral summer seasons (1 October–31 March) and the robustness of the results was confirmed.

6. Summary and conclusions

The objective of this study was to examine whether or not active and break phases in SAMS are associated with low-level wind anomalies. More specifically, we investigated the hypothesis that westerly and easterly wind regimes in the core of the Amazon basin are related to variations in large-scale convection and rainfall in South America. Comparisons of the composites shown here with previous studies reveal consistent intraseasonal patterns in convective and rainfall anomalies in SAMS. While previous studies used OLR anomalies as the reference parameter, in this study, the intraseasonal wind anomaly direction in the Amazon region is employed as the reference parameter. The region extending from Argentina toward northeast Brazil exhibits some similarity in the low-level circulation and OLR anomalies in both approaches. However, an interesting feature not shown in previous works is located over Venezuela and northwest Brazil. There, the OLR and rainfall anomalies reverse sign between W and E regimes. The recent study of Carvalho et al. (2002) investigated the activity of mesoscale convective systems in tropical and subtropical South America linked to westerly and easterly low-level wind regimes during the TRMM–LBA experiment. The northwest region in SAMS was subjected to the most significant contrasts in the convective systems (CS) characteristics observed with infrared *Geostationary Operational Environmental Satellite-8* (*GOES-8*) images. During E regimes (or break periods), the enhancement of CS in the northwest and decrease in southeast Brazil resemble the autumn season. The CS properties such as number of CS, diurnal distribution,

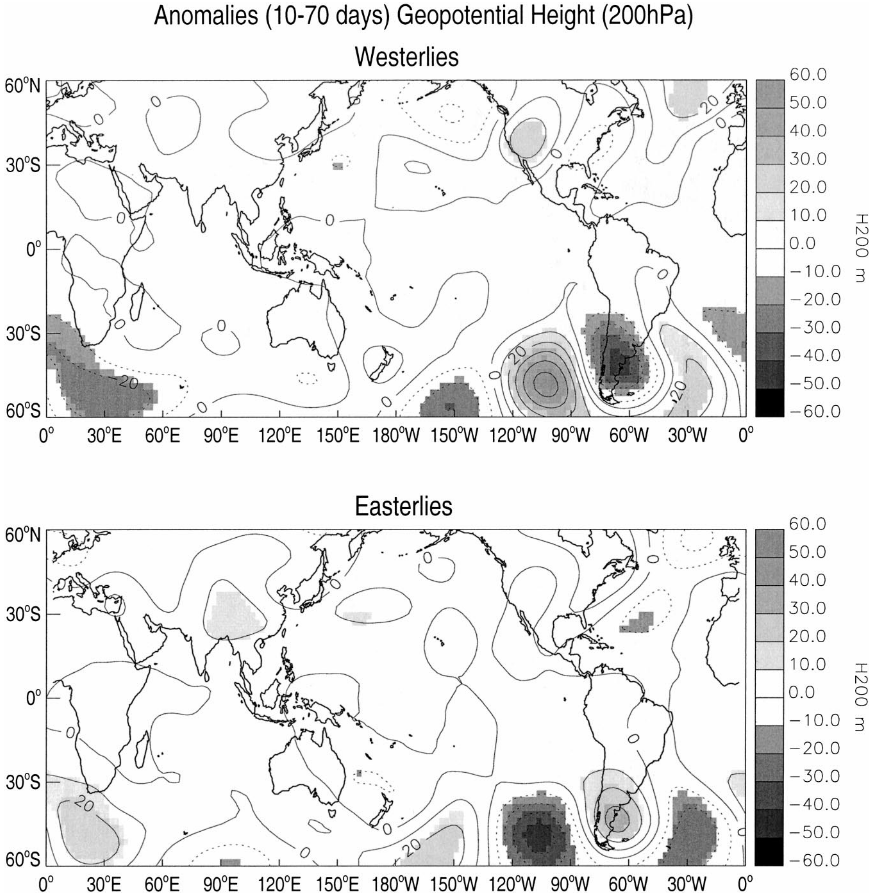

FIG. 9. Composites of H200 anomalies (contours) during (top) westerly and (bottom) easterly wind regimes. Solid (dotted) contours indicate positive (negative) anomalies. Contour interval is 10 m. Positive (negative) anomalies statistically significant at 95% level are indicated by light (dark) shading.

radius, fraction of cold tops, and fragmentation were modulated by wind anomalies in the southeast as well.

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