Large-scale index for South America Monsoon (LISAM)

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1. Introduction

Monsoon regimes occur in many regions of our planet. The term ‘monsoon’ often refers to a seasonal reversal of the large-scale circulation driven by a differential gradient between oceans and continents (Ramage, 1971; Zhou and Lau, 1998; Grimm et al., 2005; Vera et al., 2004). The seasonal cycle of precipitation over tropical South America presents the main characteristics of a monsoon regime, with distinct wet and dry seasons between latitudes 15°S to 25°S. About 50% of the annual precipitation over tropical and subtropical South America occurs during the austral summer (December–February) mostly as convective precipitation with large diurnal variability (Gan et al., 2004).

On the basis of the seasonal characteristics of circulation, Zhou and Lau (1998) showed the existence of a regional regime of summer monsoon induced by strong diabatic heating over the Bolivian Plateau. Although the easterly circulation prevails over tropical Atlantic and northern South America during the whole year, when the annual mean is removed from the summer and winter circulation composites, there is evidence of seasonal reversals in the low-level wind anomalies. Thus, Zhou and Lau (1998) demonstrated that the summer season in South America contains the main ingredients to be characterized as a monsoon regime. Moreover, it has been shown (Sugahara, 1991; Zhou and Lau, 1998; Carvalho et al., 2002; Jones and Carvalho, 2002; Carvalho et al., 2004) that intraseasonal oscillations modulate the intensity of convection and circulation during the summer monsoon. Active (break) phases of monsoon have been observed along with westerly (easterly) low-level wind intraseasonal anomalies over tropical central-eastern South America (Carvalho et al., 2002; Jones and Carvalho, 2002). Active and break phases have been documented in the monsoon regimes in Asia and Australia (e.g. Vera et al., 2006).

The correct characterization of the onset, demise and intraseasonal variations of the South American Monsoon System (SAMS) has important social and economical impacts. Great efforts have been made to properly define the onset and demise of SAMS (e.g. Kousky, 1988; Liebmann and Marengo, 2001; Wang and Fu, 2002; Gan et al., 2004, 2006). Most methods use either outgoing long wave radiation (e.g. Kousky, 1988) or precipitation (e.g. Liebmann and Marengo, 2001). Liebmann and Marengo (2001) determine SAMS onset and demise based on the time-variability of the integral of daily increments (S\text{day}) of the seasonal precipitation anomalies (annual mean removed) between two dry seasons. The advantage of this method is that it is simple and depends only on precipitation. Nevertheless, the onsets and demises are defined according to changes in S\text{day} curvature and, therefore, cannot be used in real time. Gan et al. (2006) investigated four indices to determine onsets, demises and intraseasonal variations of the monsoon over Central-West Brazil. The authors suggested that indices based on low-level circulation (850 hPa) are more efficient for these purposes, in comparison with similar indices obtained with precipitation.

In the present study, we examine the application of Combined Empirical Orthogonal Functions (EOFc) to obtain a single index that incorporates important dynamical mechanisms associated with SAMS and characterizes its large-scale features and intraseasonal to interannual variability.

2. Data and methodology

Pentad (five days average) precipitation estimates (\textit{P}) from the Global Precipitation Climatology Project (GPCP) (Xie et al., 2003), low-level (850 hPa) specific humidity (\textit{q}), air temperature (\textit{T}), zonal (\textit{u}) and meridional (\textit{v}) wind components from NCEP/NCAR reanalysis (Kalnay et al., 1996) are examined during...
The monsoon index proposed here has several important purposes: (1) representation of the large-scale spatial features of SAMS; (2) continuity in time for the evaluation of the onset and end of the summer monsoon and assessment of the characteristics of the dry season; (3) efficiency in identification of break and active phases and realistic representation of interannual variations of SAMS. To accomplish these goals, we follow the rationale of Zhou and Lau (1998) to characterize the monsoon regime and combined EOF analysis were performed using anomalies (climatological annual mean removed) of the variables described above. With this approach, the combined EOFc patterns and respective time coefficient (tcoefc) represent the seasonal covariability of the most important variables that have been related to monsoon regimes (Zhou and Lau, 1998; Gan et al., 2006). Details on the combined EOF methodology are discussed in Wilks (1995) and references therein.

3. Results

The first EOFc mode (EOFc-1) explains 23% of the total variance and is statistically independent of other modes according to North et al. (1982) criterion. Figure 1 shows the patterns of correlations obtained between the time coefficient of EOFc-1 (tcoefc) and the respective anomalies (removing the climatological annual mean) of $P$ (Figure 1a), $q$ (Figure 1b), $u$ (Figure 1c), $v$ (Figure 1d) and $T$ (Figure 1e). Important features have been identified from the EOFc patterns in Figure 1 that clearly characterize SAMS and its spatial variability. With respect to precipitation (Figure 1a), positive correlations are observed over large areas of tropical South America organized in a northwest–southeast orientated band that resembles the South Atlantic Convergence Zone (SACZ). Near equatorial Atlantic, positive correlations are observed in association with the Intertropical Convergence Zone.

High positive correlations with $q$ (Figure 1b) are observed over eastern tropical South America extending toward subtropical Atlantic Ocean, which is also consistent with the presence of the SACZ (Kodama, 1992). In association with $P$ and $q$ patterns, a dipole in the correlations between EOFc-1 and $u$ anomalies is observed (Figure 1c). That is, the seasonal enhancement (weakening) of $P$ and $q$ over tropical South America occur along with westerlies (easterlies) over north and central Brazil and easterlies (westerlies) over southern Brazil. Northerly (southerly) seasonal wind anomalies over northern and northeastern South America, indicated by negative correlations (Figure 1d), are observed along with the organization (demise) of SAMS. They indicate the importance of the transport of humidity from tropical/equatorial latitudes toward South America, which is a key aspect of the SAMS regime (Zhou and Lau, 1998). The pattern of correlations with temperature (Figure 1e) shows that SAMS is associated with strong seasonal positive anomalies in the subtropics and coastal areas of eastern South America and South Atlantic Ocean.

In summary, EOFc-1 represents the main features related to the organization and establishment of SAMS over tropical South America (Zhou and Lau, 1998, Vera et al., 2006). The patterns of correlations of Figure 1 suggest that tcoefc-1 can be used as an index to characterize the time evolution of SAMS, that is, its intraseasonal to interannual variability. For this reason, tcoefc-1 will be henceforth referred to as large-scale index for South America monsoon (LISAM).

3.1. SAMS onset and demise

Figure 2 shows some examples of the temporal evolution of LISAM for two distinct periods: 1983–1986 (Figure 2a) and 2002–2005 (Figure 2b). LISAM clearly shows an annual cycle with fluctuations on short time-scales. The onset (end) of the rainy season is defined when the three-pentad (15 days) moving average of LISAM (Figure 2) becomes positive (negative). The duration of the rainy (dry) season is defined as the length in pentads between the dates of onset and demise.

Interannual variations of the onset, demise and duration of the rainy season for the entire period are shown in Figure 3. The LISAM average onset and respective standard deviation is on pentad 61 (October 28 – November 1) ±2 pentads. The earliest onset is observed on pentad 58 (October 13–17) and occurred in the 1983–1984, 1985–1986, 1990–1991 and 2001–2002 seasons (Figure 3a). The latest onset is observed on pentad 64 (November 12–16) and occurred in the 2004–2005 and 2005–2006 seasons (Figure 3a).

LISAM average demise is on pentad 24 (April 26–30) ±1. The earliest end of the rainy season is observed on pentad 20 (April 5–10) in the 1998–1999 season and the latest on pentad 27 (May 11–15) in the 1983–1984 season (Figure 3b). The average duration, defined as the number of consecutive pentads between onset and end of the rainy season (Figure 3c) is 37 ± 2 pentads. The longest duration was observed in 1998–99 (41 pentads), whereas the shortest duration was observed in 1983–1984 (31 pentads).

Previous observational studies have reported that the rainy season begins in September over equatorial Amazon and progresses southeastward, such that by the end of September and beginning of October the rainy season starts over southeastern South America (Vera et al., 2006). The study of Gan et al. (2004) indicates that, on average, the onset and demise of the summer monsoon over central-western Brazil (1979–2000) occur approximately two pentads earlier than observed with LISAM, with standard deviations ±3 and ±2 pentads, respectively. The average
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Figure 1. First EOFc-1 patterns described as correlations between tcof-1 and anomalies (annual mean removed) of (a) GPCP precipitation, (b) specific humidity, (c) zonal wind (d) meridional wind and (e) air temperature. Variables in Figures (b)–(e) are obtained at 850 hPa. Shades indicate statistically significant correlations at 5% significance level. The number of independent events is equal to the number of seasons (i.e. 26 events)

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duration of the rainy season in that work is about 38 ± 3 pentads, which is one pentad longer than estimated with LISAM. The differences in the two methods are likely due to the fact that LISAM is not restricted to central-western Brazil, but represents the summer monsoon over the entire tropical South America (Figure 1). Nevertheless, about 90% of the total annual precipitation over central-western Brazil occurs
Figure 2. Examples of the time evolution of LISAM (thin solid line) for: (a) 1983/84, 1984/85, 1985/86 and (b) 2002/03, 2003/2004, 2004/05. Heavy solid lines are 3-pentads LISAM moving averages.

Figure 3. Annual variability of the onset (a), end (b) and duration (c) of the summer monsoon. The dashed line represents the mean value.
during the average summer monsoon determined with LISAM, in agreement with Gan et al. (2004) (not shown).

3.2. Sensitivity tests

Sensitivity tests were performed to investigate the importance of excluding variables to estimate SAMS' onset, demise and duration using EOFs. Table I summarizes the results. The tests were performed such that at least one variable was excluded of the analysis in each step (Table I, first column) and the correlation between the new time coefficient and LISAM was computed. The annual cycle of the time coefficient was removed and correlations were obtained between high-frequency (short period) variability of LISAM and of the new tcoef-1 (Table I, last column). In all cases, EOFc-1 is statistically independent of the others (North et al., 1982).

It is interesting to note that removing q from the analysis yields basically no modifications in tcoefc-1 if P, u, v and T are kept. This is likely because q and P are strongly related, in comparison with the other variables. The importance of this result is that P can be substituted by q without losing a significant fraction of SAMS variability (correlation equal 0.90). It means that the analysis could be potentially extended to periods when precipitation data are not available, as long as other reanalysis fields (T, u, v, q) are used. Precipitation alone provides the latest onsets and demises and show low correlation (0.51) with LISAM. Early onsets (5 pentads) and demises (one pentad) and short ‘monsoon’ duration (5 pentads) are observed when circulation (u, v) is used alone, suggesting that changes in anomalies of circulation precede the actual establishment and also the demise of the monsoon. Seasonal variations of T are high and coherent in the subtropics and, thus, the presence of T in the analysis increases the total variance explained by EOFc-1 (e.g. 23% for LISAM against 18% with P, u, v and q), although changes in the onset and demise are not significant.

Including upper-level variables such as u and v in 200 hPa decreased (increased) the magnitude of the EOFc-1 correlations with all variables over central (southern) Brazil. On the other hand, adding new variables that are well correlated in EOFc analysis is not worthy, since this operation requires advanced computational resources with no significant changes in the results. Thus, LISAM is defined with the set of variables described in the first row of Table I because they provide the best spatiotemporal patterns to characterize SAMS.

3.3. Intraseasonal variability

Figure 2 indicates that, in addition to a pronounced annual cycle, LISAM shows high-frequency variations. To investigate this issue further, spectral analyses of LISAM were performed during the rainy seasons (October–March). For this purpose, the LISAM mean annual cycle (26 years average) was removed and the spectrum was obtained as the ensemble of 25 seasonal spectra of the LISAM anomalies (LISAManom). For details on the spectral ensemble methodology, the reader is referred to Jones et al. (1998). LISAManom summer spectrum shows a statistically significant peak on intraseasonal timescales (30–60 days) (Figure 4). This peak is consistent with the Madden–Julian oscillation (Madden and Julian, 1994), which is known to play an important role in modulating convection over eastern South America during the summer (Carvalho et al., 2004; Jones et al., 2004). These results suggest that EOFc-1 and, therefore, LISAM retain fluctuations of SAMS’ regime on intraseasonal time-scales. It is worth mentioning that intraseasonal variations on 15–20 days are retained by the second EOFc (EOFc-2). The EOFc-2 spatial pattern shows high correlation with P over the oceanic portion of the SACZ (not shown).

### Table I. Comparisons of average onset, demise, duration, explained variance (%) observed with EOFc-1 performed with distinct set of variables (indicated in the first column). Correlations (last column) are relative to the EOFc performed with all variables (P, u, v, q, T) used to define LISAM

<table>
<thead>
<tr>
<th>Variables</th>
<th>Onset (pentad)</th>
<th>Demise (pentad)</th>
<th>Duration (pentads)</th>
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<tbody>
<tr>
<td>P, u, v, q, T</td>
<td>61</td>
<td>24</td>
<td>37</td>
</tr>
<tr>
<td>P, u, v, T</td>
<td>61</td>
<td>24</td>
<td>37</td>
</tr>
<tr>
<td>u, v, q, T</td>
<td>60</td>
<td>24</td>
<td>36</td>
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<tr>
<td>P, u, q, T</td>
<td>61</td>
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<tr>
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</tr>
<tr>
<td>P</td>
<td>65</td>
<td>26</td>
<td>39</td>
</tr>
</tbody>
</table>

Figure 4. Ensemble spectrum of LISAM anomalies during the rainy season (1979–2004) (thick solid line). Thin solid line is the red-noise spectrum and the dashed line the 95% confidence level.
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Figure 5. Difference in the composites (LISAM$_{\text{anom}}$ upper quartile – lower quartile) of precipitation (a) and 850 hPa wind (b) observed during the summer (November–March). Shades indicate statistically significant differences at 5% significance level. Degrees of freedom are estimated based on the number of independent events.

To further verify the relationships between active and break phases of SAMS and LISAM$_{\text{anom}}$, summer pentads corresponding to the upper (75th) and lower (25th) percentiles of LISAM$_{\text{anom}}$ were selected. Composites of the upper and lower quartiles of $P$, $u$ and $v$ were performed and differences are shown in Figure 5.

The differences in the composites of precipitation (Figure 5a) indicate statistically significant enhancement (suppression) of precipitation for events corresponding to LISAM$_{\text{anom}} \geq$ upper (\leq lower) quartile over large areas of tropical South America, extending from central Amazon toward southeastern Brazil, in association with the SACZ. These features are observed along with suppression (enhancement) of precipitation over southern Brazil and northwestern South America. In addition, variations in low-level circulations (Figure 5b) indicate the enhancement of westerlies (easterlies) over tropical central-eastern South America and the strengthening (weakening) of the northerlies over northern South America for LISAM$_{\text{anom}} \geq$ upper (\leq lower) quartile. Precipitation (Figure 5a) and wind (Figure 5b) differences over South America and Pacific and Atlantic oceans are consistent with intraseasonal activity during the summer monsoon, as previously shown in Jones and Carvalho (2002) and Carvalho et al. (2002). These variations in circulation and convection have been previously related to active and break phases of the monsoon regime and are associated with the propagation of midlatitude wave-trains on intraseasonal time-scales (Jones and Carvalho, 2002).

4. Conclusions

Combined EOFc of anomalies of $P$, $q$, $u$, $v$ and $T$ at 850 hPa was successfully applied to obtain a single index that describes large-scale features and intraseasonal to interannual variations of SAMS. The advantage of this method is that LISAM is continuous in time and, therefore, is defined during dry and wet seasons. In addition, it does not depend on past observations and, thus, can be used to diagnose the state of the monsoon in real time. LISAM retains variations on intraseasonal time-scales (30–60 days), which are related to breaks and active phases of SAMS. Sensitivity tests showed that including fewer variables might affect the onset in about 1–6 pentads. The largest differences occur when circulation is considered with no inclusion of precipitation or specific humidity. Increasing the number of correlated variables does not add significant changes in the characterization of SAMS. However, the replacement or the use of fewer variables to perform EOFc may cause significant differences on intraseasonal time-scales.

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