Extreme Precipitation Events in Southeastern South America and Large-Scale Convective Patterns in the South Atlantic Convergence Zone

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ABSTRACT

The occurrence of daily extreme precipitation events in southeast South America (São Paulo, Brazil) and the spatial features of convective activity in the South Atlantic convergence zone (SACZ) are investigated. Precipitation data from surface stations in São Paulo state from 1979 to 1996 are used to determine the frequency of occurrence of extremely heavy daily precipitation events. Daily averages of outgoing longwave radiation (OLR) are examined to characterize convective activity in the SACZ. OLR features are identified with factor analysis. Two factors explain ~65% of the total variance of the convective activity patterns in tropical South America and characterize events according to the intensity and extent of the OLR features over the Atlantic Ocean. The combination of factors indicates that 35% of extreme precipitation events occurred when convective activity in the SACZ was intense over large parts of tropical South America, which includes São Paulo, but with less extent toward the Atlantic Ocean. Warm SST episodes (El Niño) seem to modulate the occurrence of extremes associated with intense convection in the SACZ displaced northward of São Paulo and toward the Atlantic Ocean. The remaining events associated with weak convective activity in the SACZ suggest the role of transient systems producing extreme precipitation in São Paulo. The important contribution of the present work is the documentation of the role of orographic features for the regional distribution of extreme precipitation in São Paulo. It is shown that the regional distribution of extreme precipitation depends on both the intensity and form of the convection in the SACZ.

1. Introduction

Heavy precipitation events have unquestionably one of the largest economic and social impacts of any atmospheric phenomena. Floods are systematically observed in association with these infrequently occurring events, especially in urban areas where the drainage may be inadequate to accommodate a sudden large amount of rainfall. Likewise, in rural regions crops and livestock can suffer damage from excessive precipitation. In addition, a few events can affect the local seasonal totals and therefore the management of the freshwater supply. The relevance of understanding the mechanisms for which the atmosphere operates to produce heavy or extreme precipitation is obvious. Moreover, given the complexity of causes of such events over a season or year, the necessity of a detailed examination of different aspects of the phenomenon is evident. The focus of the present study is on the role of large-scale convective features over tropical southeastern South America in the daily extreme precipitation events in São Paulo, Brazil. Broadening the knowledge of the environmental conditions associated with extreme precipitation events is especially relevant for São Paulo because it is the most populous state in Brazil, with more than 90% of its 31.5 million inhabitants living in urban environments (the highest urban human concentration in South America).

The investigation of extreme precipitation events on regional scales is a complex task. Topography and local circulation can enhance the activity of mesoscale con-
The climatology of precipitation over tropical and subtropical South America, which includes São Paulo, shows a regular annual cycle. Convective activity begins in the western Amazon basin in early August and marches southeastward. The wet season in São Paulo peaks in the western Amazon basin and extends southeastward into the Atlantic, passing above the region considered to be "southeast" Brazil (Satyamurty et al. 1998; Liebmann et al. 1999). São Paulo is considered to be the southernmost state in that geographical region and therefore is under influence of the SACZ.

Liebmann et al. (2001) demonstrated a link between sea surface temperature (SST) anomalies and the count of extreme events during summertime in São Paulo. In that work, an extreme event at an individual station is defined when a certain percent of the seasonal climatological total at that station fell in one day. The SACZ is known to play an important role in determining the mean annual rainfall in southeast Brazil (e.g., Nogueira-Paegle and Mo 1997; Lenters and Cook 1999; Paegle et al. 2000). However, precipitation in the SACZ exhibits a rich variety of intraseasonal variations. Additionally, one can envision a scenario in which most extreme events occur in association with squall lines, mesoscale convective complexes, or other types of mesoscale systems. These events, on the other hand, may be quasi-independent or may occur during the most active or weak periods of the SACZ. Therefore, an important question needs to be investigated: Do variations in the spatial characteristics of the deep convective activity in the SACZ modulate extreme events in southeast South America?

The objective of the present study is to investigate the relationships between the occurrences of extreme precipitation events in São Paulo and the intensity and extent of the SACZ deep convection to the Atlantic Ocean. In this context, we investigate the role of orographic features in the regional distribution of extreme precipitation in São Paulo.

2. Data

The rainfall data used in this study are the same as in Liebmann et al. (2001) and were provided by the Departamento de Águas e Energia Elétrica (DAEE) of São Paulo. The data consist of daily totals from 234 stations in São Paulo from 1979 to 1996. In this analysis, individual records are employed. Daily outgoing longwave radiation (OLR) is used to characterize large-scale aspects of tropical convection (Liebmann and Smith 1996). The large-scale circulation, temperature, and humidity are described in this study with National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996). Daily winds (850 and 200 hPa), and OLR anomalies with 2.5° of horizontal resolution are used. Anomalies are obtained by first removing the daily climatology and then applying a 5-day running mean.

3. Definitions and methodological approaches

a. Extreme precipitation events

The definition of extreme precipitation is similar to that of Liebmann et al. (2001). For any given station,
an extreme event is defined when 20% or more of the seasonal climatological total at that location fell in one day. Only the [December–January–February (DJF)] season is considered. According to this criterion, 214 extreme rainfall observations were reported over 115 stations during 1979–96. They occurred in 146 days or events, with the annual distribution shown in Fig. 1. As indicated in that figure, the 20% threshold criterion selected extreme precipitation events that occur in São Paulo every year with a median frequency of 8 days (that is, a day with an extreme event at any station occurred less than 10% of the season). Also included in Fig. 1 is a qualitative description of the DJF SST in the Niño-3.4 region (5°N–5°S, 120°–170°W) provided by the NCEP Climate Prediction Center (CPC). Although the period considered here is not long enough to describe interannual variability of extreme events related to ENSO, some aspects are noteworthy. There are nine warm and eight cold/neutral episodes in the period. If one (arbitrarily) excludes the weak 1992/93 episode (in which there were 5 events), there are 43% more extreme events in the remaining 8 warm years (83 events) than during cold/neutral years (58 events). There are four cold episodes, and except for the 1987/88 event, the number of extreme events during cold episodes was below the median. The relevance of this discussion in the present work is to indicate that the threshold adopted and the period analyzed preserves the characteristics observed in Liebmann et al. (2001).

b. Convective activity in tropical and subtropical South America and the SACZ

Figure 2 shows the DJF mean daily rainfall and 850-hPa winds, and indicates maximum precipitation in the Amazon basin extending toward southeast Brazil. Note that the precipitation field is obtained from stations in Brazil. The spatial configuration of precipitation is consistent with the frequency of grid points with daily average OLR $\leq 200$ W m$^{-2}$ shown in Fig. 3 (top). Contours in this figure indicate the percent of occurrence of grid points with OLR $\leq 200$ W m$^{-2}$ from 1979 to 1996 (DJF). Only percentages above 30% are shown. They imply that deep convective activity is more frequent (more than 50% of the observations) over the central Amazon. Asterisk symbols represent the coordinates of the stations in São Paulo where extremes have been observed. These stations cover practically the entire state (cf. the inset map). The location of stations and the topography in São Paulo are also shown in Fig. 3.
Fig. 3. (top) OLR$_{200}$ frequency climatology for 1979–96 (DJF). Contours represent frequency (%) of grid points with OLR $\leq 200$ W m$^{-2}$. Frequencies $\geq 50\%$ are shaded. Asterisks show the coordinates of DAEE stations in São Paulo (indicated in the inserted map) used for the definition of extreme precipitation events. Dotted lines specify regions where the tropical convective activity associated with the SACZ is investigated. (bottom) Topography and localization of stations in São Paulo. Dashed lines and labels indicate main orographic features in São Paulo. The dashed curves in this figure separate the stations according to altitude and the main orographic features in São Paulo. They were determined based on the spatial stratification of total annual rainfall in São Paulo as shown in Fig. 2 of Liebmann et al. (2001). Serra do Mar is a coastal mountain range with a southwest–northeast orientation and an average altitude ranging from 700 to 1200 m. The highest peaks are observed on the north coast between Rio de Janeiro (RJ) and São Paulo. The Serra da Mantiqueira mountain range separates the states of Minas Gerais (MG) and São Paulo. The Mantiqueira’s highest altitudes (above 1200 m) are observed northeast of São Paulo and southeast of MG. Topographic altitudes decrease from the coast toward the Paraná River valley, west of São Paulo. The relationships between the occurrence of extreme precipitation and orographic features will be explored later in this paper.

The SACZ has been observed as an elongated band of high convective activity emanating from the Amazon region and running toward the ocean (Satyamurty et al. 1998; Fig. 3, top). The SACZ is also generically described as the region with high variability of convective activity (Fig. 4) during summertime in eastern South
Fig. 4. OLR std dev for 1979–96 (DJF) (W m$^{-2}$). Dotted lines as in Fig. 3 (top).

Table 1. Area extent of regions defined to search for OLR features (dashed lines in Fig. 2). The São Paulo area is indicated for comparison.

<table>
<thead>
<tr>
<th>Region</th>
<th>Area (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon</td>
<td>2.118 50 × 10$^6$</td>
</tr>
<tr>
<td>Coastal</td>
<td>2.346 79 × 10$^6$</td>
</tr>
<tr>
<td>Ocean</td>
<td>1.541 70 × 10$^6$</td>
</tr>
<tr>
<td>São Paulo (SP)</td>
<td>2.488 09 × 10$^5$</td>
</tr>
</tbody>
</table>

To understand the importance of the spatial characteristics of tropical and subtropical convective activity over the continent and Atlantic Ocean during extreme precipitation events in São Paulo and to be consistent with the SACZ description, we focused our analysis on the OLR features that intercepted the noncontiguous areas indicated with dashed lines in Fig. 3 (top) and Fig. 4. For the sake of simplicity, we named these regions Amazon, Coastal, and Ocean. The Amazon was defined in the region of maximum convective activity (Fig. 3, top) and local minimum subseasonal variance (Fig. 4). The Coastal in southeast Brazil and Ocean regions are characterized by maximum subseasonal OLR variance (Fig. 4). Table 1 summarizes the area extent of these regions in comparison to São Paulo.

To examine the spatial and structural characteristics of the large-scale deep convective activity in the SACZ, contiguous regions of OLR $\leq 200$ W m$^{-2}$ were identified. Only those regions that intercepted the Coastal area were selected (hereafter referred to as OLR$_{200}$). This assumption eliminated high-latitude synoptic systems or disturbances propagating in the intertropical convergence zone that do not enter the Coastal region. The MASCOTTE algorithm (Carvalho and Jones 2001) was used to examine spatial and temporal characteristics of the selected OLR$_{200}$ cases. The following properties were determined for each OLR$_{200}$: area (Area), eccentricity (Ecc), minimum OLR (OLR$_{min}$), fraction of OLR$_{min}$ (%OLR$_{min}$), and OLR spatial variance (VarOLR). The parameter %OLR$_{min}$ was defined as the ratio between the number of grid points with OLR$_{min}$ to the number of grid points with OLR$_{200}$. Ecc is defined as the ratio between the minor axis and major axis of each OLR$_{200}$ feature. For this reason, large (small) values of Ecc imply a more circular (linear) OLR$_{200}$ aspect.

Because the OLR$_{200}$ may intercept the Amazon and/or Ocean regions and this is important to identify SACZ spatial properties, the fractions of OLR$_{200}$ in each of the three regions shown with dotted lines in Figs. 3 and 4 were computed (%Amazon, %Coastal, and %Ocean, respectively). Note that with this definition, extensive OLR$_{200}$ can have part of its area outside the Coastal domain and therefore small %Coastal values (the opposite situation applies when OLR$_{200}$ is narrow and entirely contained in the Coastal area). Furthermore, because Coastal, Ocean, and Amazon are noncontiguous domains, one should not expect that the sum of OLR$_{200}$ fraction in each domain is 100%.

Additional details about the algorithm to determine OLR$_{200}$ structural properties are presented in Carvalho and Jones (2001). Physical interpretations of these properties in the context of large-scale convective activity features will be discussed in the following sections.

c. Determination of OLR patterns in the SACZ

The categorization of large-scale convective activity in the SACZ was performed by considering the OLR$_{200}$ structural properties discussed above. With these properties, it is possible to distinguish patterns of OLR$_{200}$ by incorporating both extent (Area) and intensity of convective activity (OLR$_{min}$, %OLR$_{min}$, VarOLR). Moreover, the Ecc parameter provides information about the roundness of the OLR$_{200}$ features, which in combination with %Amazon, %Coastal, and %Ocean, allows the discrimination of events when the SACZ resembles the definition of Satyamurty et al. (1998). We selected 1576 days in the period 1979–96 (DJF) as case studies with OLR$_{200}$ intercepting the Coastal region. Extreme events of precipitation in São Paulo were observed in 146 days of that sample. Factor analysis was then applied to objectively determine categories of SACZ convective activity according to its structural and intensity properties. Similar methodology has been used with the purpose to identify mesoscale patterns of clouds using infrared satellite images (Carvalho and Silva Dias 1998). The factor analysis in the present study was performed with all OLR$_{200}$ structural properties discussed previously. The underlying principle is that each event can be considered as an individual observation of an OLR$_{200}$ feature associated with a pattern of convective activity in the SACZ, which in turn defines a given category. The input for the factor analysis is therefore a time series represented by the matrix.
Area and %Coastal indicates that extensive OLR200 regions have a large fraction of their area outside the Coastal domain. OLRmin, with the same sign as %OLRmin and opposite to Area indicates that the larger OLR200, the colder OLRmin. The region with very cold OLRmin does not cover a large fraction of the OLR200, which increases the OLR variance (OLRmin and %OLRmin with opposite sign to VarOLR). The opposite situation is observed when the SACZ is weak. Therefore, factor 1 is related to the intensity and extent of deep convection in the SACZ and its physical interpretation can be clearly observed in daily OLR maps. Negative (positive) factor-1 scores indicate SACZ with intense (weak) convective activity and large (narrow) extent. Factor 2 explains ~19% of the total variance and shows large weighting on Ecc and %Ocean, with opposite sign (negatively correlated). Consequently, factor 2 is related to the spatial shape of the deep convection in the SACZ, with negative (positive) factor-2 scores indicating oceanic (and elongated) or continental (and concentric) aspects of the OLR200. The physical interpretation of each factor is summarized in Table 2 next to the respective factor loadings.

Figure 5 summarizes the properties of the distribution of factor 1 (top) and factor 2 (bottom) such as median, lower (25th), and upper (75th) quartiles, the interquartile range, and maximum and minimum factor scores, separated in two distinct datasets: OLR200 observations along with the occurrence of extreme precipitation events in São Paulo (146 cases) and “others.” To compare the distributions with equal number of cases, the others sample contains 146 randomly selected cases obtained from the complete dataset with no extreme precipitation observed. The factor-1 scores distribution (Fig. 5, top), which is related to the intensity and extent of deep convection in the SACZ, shows distinct characteristics for the two samples. The interquartile range and the maximum score obtained from the sample with extreme precipitation events are displaced toward negative values, which is indicative of enhancement of con-
Fig. 5. Characteristics of the distributions of (top) factor-1 and (bottom) factor-2 scores for 146 days with extreme precipitation events and 146 days with no register of extreme events by the stations in São Paulo. Outliers are data point values $1.5$ times the interquartile range. The most extreme factor scores are data point values $3.0$ times the interquartile range.

The focus of the present discussion is on the interpretation of patterns of convective activity in the SACZ extracted from factor analysis and relationships with extreme precipitation events in São Paulo. Since the two factors are associated with distinct and independent aspects of the OLR$_{200}$, namely, intensity and form (Table 2), their combination characterizes the actual pattern of deep convective activity in the SACZ in association with extreme precipitation events in São Paulo. With this rationale, further analyses were performed by grouping events in four categories based on the combination of factors signals. The resulting categories are labeled as follows: intense-oceanic (factor 1 $> 0$ and factor 2 $< 0$), intense-continental (factor 1 $< 0$ and factor 2 $> 0$), weak-oceanic (factor 1 $> 0$ and factor 2 $< 0$), and weak-continental (factor 1 $> 0$ and factor 2 $> 0$). Interpretation of the spatial characteristics of convection in the SACZ classified in each category discussed above along with the investigation of daily anomalies of OLR, wind (850 and 200 hPa), are shown in Figs. 6–9 and examined in detail in the following sections.

1) Extreme events associated with weak SACZ activity

(i) Weak-oceanic category

This category was associated with only 13% of the 146 events of extreme precipitation in São Paulo, the lowest fraction of all categories. Two days prior to the occurrence of extreme events in this category (Fig. 6a), negative anomalies are observed over São Paulo extending to the Atlantic Ocean, which indicates the presence of a frontal system in this region. Positive OLR anomalies are observed over Uruguay, northeast Brazil, running to the Atlantic, and north of the Amazon basin. As the frontal system moves northeastward one day prior to the events (Fig. 6b), convective activity (negative anomalies) observed before over São Paulo, moves to the São Paulo coast and the ocean also affecting RJ. For lag equal to zero (Fig. 6c), negative anomalies increase near the coast, in the boundaries with RJ where the Serra do Mar mountain range has its highest elevation (see Fig. 3, bottom). Positive OLR anomalies indicating sup-
pressed convection are observed in a large part of central and northeast Brazil, and eastern Argentina (Fig. 6c). One day after the occurrence of extreme precipitation in São Paulo in this category, there is no longer a clear indication of the frontal system (Fig. 6d), although suppression of convection (positive OLR anomalies) can be verified in large areas of the Amazon basin and central Brazil.

The 850-hPa wind anomalies (Fig. 6e) for lag equal to zero show an anomalous anticyclonic circulation near the southeast coast, with dominant northeasterly anomalies over São Paulo. The southeastern branch of the anomalous anticyclonic circulation is observed over the ocean, veering westward as the flow enters the northeast coast of Brazil in a perpendicular orientation (Fig. 6e).

The characteristics of deep convection can be linked to this anomalous circulation, which favors convective activity extending toward the coast and ocean. The 200-hPa wind anomalies show the presence of anticyclonic anomalous circulation (Fig. 6f), consistent with the increase in the geopotential height (not shown), which is indicative of enhanced convection over that area.

(ii) Weak-continental category

The weak-continental pattern is associated with ~22% of the total extreme events in São Paulo, which corresponds to ~1.7 times the number of events that occurred in the weak-oceanic category. Some characteristics are indeed quite different from what is observed in the weak-oceanic category. The lag composites (Figs. 7a–d) clearly illustrate these aspects. Two days prior to the occurrence of extreme precipitation in São Paulo in this category, there is neither a clear signal of a frontal system with extension to the ocean nor any anomalous convection over the continent (Fig. 7a), although weak negative anomalies (not significant) are observed northeast of Argentina, Paraguay, and southern Brazil. One day prior to the events, anomalous convection (negative OLR anomalies) shows minimums in the continent, over central São Paulo (Fig. 7b) extending to the area south of Brazil. Extreme precipitation occurs in this category as convection grows over a large area of São Paulo (Fig. 7c; observe the −25 W m⁻² contour). Note that contours of OLR negative anomalies are very concentric, that is, the features do not resemble a frontal system. In addition, positive anomalies are observed over the Atlantic Ocean at about the same latitude as São Paulo, extending from 30° to 10°W, which is in contrast to the weak-oceanic category (cf. Fig. 6c with Fig. 7c). Suppression of convective activity over a large area of the Amazon basin and northern Brazil is also observed for zero lag (Fig. 7c). Particularly important is the nonexistence of a clear pattern of suppressed convection over southern Brazil and eastern Argentina as observed for the weak-oceanic category. For a one-day lag, the deepest anomalous convection moves northeastward of São Paulo, although negative anomalies persist for the entire area.

The low-level circulation anomalies for zero lag (Fig. 7e) also show contrasting aspects compared to the weak-oceanic category. For instance, northerly wind anomalies are observed west of São Paulo and westerly wind anomalies are observed over the entire state of São Paulo. In addition, there is no indication of the well-defined anomalous anticyclonic circulation near the coast as observed in the weak-oceanic category. (cf. Fig. 7e with Fig. 6e). Rather, the center of the anomalous anticyclonic circulation is displaced eastward over the ocean and a cyclonic feature is observed over the continent southwestward of São Paulo in association with the anomalous northwesterly flow. Another important characteristic is the anomalous cyclonic circulation at the extreme south of South America, which is related to a pool of cold air (not shown). The 200-hPa wind anomalies (Fig. 7f) indicate an anomalous cyclonic circulation collocated with the climatological position of the Bolivian high (Gandu and Silva Dias 1998), which is a consequence of its weakening. The 200-hPa southern anomalous circulation in the western Atlantic (north-eastward of São Paulo) is possibly linked to the suppression of convection over the ocean and enhancement over southeastern Brazil.

2) Extreme Events Associated with Intense SACZ Activity

(i) Intense-oceanic category

The intense-oceanic category corresponded to 30% of the total extreme events recorded in São Paulo. Lag composites of OLR anomalies (Figs. 8a–d) indicate an SACZ intensification and extension to the Atlantic Ocean. Two days prior to the occurrence of extremes in São Paulo (Fig. 8a), one can observe the signal of anomalous convective activity over the states north of São Paulo. One day before the events (Fig. 8b), an intensification of convective activity is observed, extending from central Brazil to the Atlantic Ocean, passing through São Paulo. Positive anomalies are clearly observed south of the SACZ, with a center collocated with
Fig. 7. Same as Fig. 6 but for weak-continental patterns.
FIG. 8. Same as Fig. 6 but for intense-oceanic patterns.
Fig. 9. Same as Fig. 6 but for intense-continental patterns.
the Atlantic Ocean can be observed approximately at a statistically significant increase of the westerlies over and weak-oceanic categories, respectively. In addition, of the corresponding location in the weak-continental center approximately at 30°S and east of 40°W, this conﬁguration of the low-level wind anomalies results from the extension of the deep convection toward the Atlantic Ocean. Noticeable also are the easterly anomalies extending from the tropical Atlantic to the eastern tropical Paciﬁc, which is opposite to the weak-oceanic category. Moreover, the 200-hPa wind anomalies (Fig. 8f) are additional evidence of the enhancement of convection over the western tropical Atlantic and suppression of convection in midlatitudes over eastern Argentina and Uruguay.

(ii) Intense-continental category

This category represents the large-scale pattern associated with most extreme precipitation events observed in São Paulo, which corresponds to about 35% of the total events (5% more than for the intense-oceanic cases). Although this category is related to intense/extensive convective activity in the SACZ, there are notable differences of OLR anomalies and circulation patterns compared to intense-oceanic characteristics. The lag composites (Figs. 9a–d) indicate that two days prior to the occurrence of extreme precipitation in São Paulo (Fig. 9a) negative anomalies are observed over the continent in a large portion of the central Amazon and eastern Brazil. One day prior to the events (Fig. 9b) convective activity increases north of São Paulo (in MG) along with the enhancement of negative anomalies north of Brazil, possibly related to the convective activity in the ITCZ. For zero lag (Fig. 9c), convective activity increases over the entire area of São Paulo (observed OLR anomalies are less than −25 W m⁻²). Note that convective activity is also enhanced over the southwestern Amazon, north-northeast of Brazil, and over the equatorial Atlantic extending toward western Africa. This feature is possibly related to the enhancement of the convective activity in the ITCZ, whose mean latitudinal position in DJF is between 5°N and 0° (Mächel et al. 1998). Positive anomalies are observed over the central tropical Atlantic, south of Brazil, and Uruguay (Fig. 9c). For a lag of one day (Fig. 9d), convective activity decays over the eastern Amazon and São Paulo, although negative anomalies still remain over southeastern Brazil and the ITCZ. Positive anomalies are observed over the central tropical Atlantic in all lag composites for this category, which is consistent with the continental aspect of the SACZ (of opposite sign to the oceanic features).

The 850-hPa low-level anomalies for zero lag (Fig. 9e) indicate an increase of the northerly component of the winds in São Paulo. This wind pattern seems to be associated with an enhanced anomalous cyclonic circulation over central South America. The northerly anomalous winds favor the advection of moisture from the Tropics to a large area in São Paulo, which could generate appropriate environmental conditions for intensification of convective activity from regional to local scales (Houze 1993; and references therein). No statistically significant anomalies are observed over South America with respect to high-level winds anomalies (200 hPa; Fig. 9f). Nonetheless, a 200-hPa anomalous cyclonic circulation (Fig. 9f) is observed over the western tropical Atlantic off the northeast Brazilian coast along with cooling of the atmosphere evident in the 200-hPa anomalies (not shown). This pattern suggests the enhancement of the northeast trough (Gandu and Silva Dias 1998), which may play a role for the extent of deep convective activity toward the northern coast of Brazil (Fig. 9a; Kousky and Gan 1981). Moreover, easterly anomalies off western Africa veering northerly over the equatorial Atlantic seem to be related to the anomalous ITCZ activity.

5. Regional characteristics of extreme events

The purpose of the following discussion is to identify the relationships between patterns of deep convection in the SACZ and the regional differences in the occurrence of extreme precipitation in São Paulo. To address this issue, the following physical aspects need to be considered:

• Rainfall is a highly intermittent field and total amounts depend on the extent and duration of its stratiform
Heavy precipitation is typically associated with convective rainfall. Given the timescale of convective rainfall (minutes to hours) the maximum precipitation area may not simultaneously cover many stations. Favorable environmental conditions are necessary for formation, intensification, and propagation of new convective cells in order to affect a large region (Houze 1993). Topographic features influence the formation and intensification of convective cells, and the stationarity of convective systems (Smith et al. 1996), which can be key for the observation of large daily totals of rainfall.

To account for the spatial variability of heavy rainfall, the existence of topographic features and the implications of the nonuniform density of stations, we examined the frequency of occurrence of extreme precipitation considering each region depicted in dashed lines in the bottom of Fig. 3 (i.e., Paraná valley, low plains, high plains, coast, Serra do Mar, and Mantiqueira), separately. We recall that these regions were defined according to the variability of the mean annual total rainfall, which shows a decrease from the coast (>2000 mm) to the Paraná valley (<1000 mm), approximately following the terrain elevation. Topographic features such as Serra da Mantiqueira and Serra do Mar are characterized by maximum annual totals and strong gradients of rainfall (e.g., Liebmann et al. 2001). The total extreme precipitation events that occurred in a given region were then computed by counting the number of days that one or more stations registered an extreme event of precipitation in that region. Notice that in some cases, especially when convective activity in the SACZ is intense, extreme events may be observed in the same day in different regions (not shown). To relate large-scale features of convective activity with the spatial distribution of extreme precipitation, the total number of days with extreme events in each region was partitioned into the SACZ categories determined before. The results are shown in Fig. 10 and discussed below.

a. Intense SACZ

• Oceanic: The regional partition of the total days with extreme events associated with the intense-oceanic pattern indicates a relative uniform contribution of this category in the Paraná valley and low plains (27% of occurrences in both regions). The contribution increases in the high plains (38%) but decreases toward the coast (21%). These characteristics may be the result of low-level westerly wind anomalies over São Paulo (Fig. 8e) and the consequent increase in the advection of moisture from the Amazon basin. The configuration of low-level wind (Fig. 8e) and positive temperature anomalies over the ocean near the coast (not shown) may have caused a weakening of the sea breeze circulation (e.g., Stull 1988), which could imply less occurrence of extremes in this category in stations very close to the coast compared to the intense-continental and weak-oceanic categories. The increase in the number of days with extreme precipitation in the Mantiqueira region, however, is remarkable. The pattern of OLR anomalies for this category for zero lag (Fig. 8c) clearly shows a displacement of deep convection toward the northeast of São Paulo, where Serra da Mantiqueira has its highest elevations.

• Continental: Consistent with the largest extent of deep convective activity over São Paulo (Fig. 9c), this category shows a nearly equal contribution from the Parana valley to the high plains in São Paulo, and is almost as important as the intense-oceanic pattern for the Parana valley and low plains. The increased northerly low-level winds at the

b. Weak SACZ

• Oceanic: The number of extreme events increases from western São Paulo to the coast and Serra do Mar in this category. As it was pointed out in section 4b, convective activity in the SACZ is weak and with limited extent over South America for this category, but shows an enhancement over a large portion of the eastern coast of São Paulo (Fig. 6c). This configuration is consistent with the increase of extreme precipitation events in that area.

• Continental: This category shows a nearly equal contribution from the Paraná valley to the high plains in São Paulo, and is almost as important as the intense-oceanic pattern for the Paraná valley and low plains. The increase in the northerly low-level winds at the
eastern Andes (Fig. 7e) and the consequent transport of moisture from the Amazon to northeast Paraguay (the region known as the Chaco low) are important aspects associated with the development of mesoscale convective complexes (MCC) in subtropical South America (Velasco and Fritch 1987; Silva Dias 1987). These mesoscale systems typically have life cycles from 10 to 20 h and often cause heavy precipitation and severe weather (Maddox et al. 1982). The increase in MCC activity has been systematically observed during weak SACZ activity, the former being associated with predominant northerly low-level winds in subtropical South America (Silva Dias 1987; Nieto-Ferreira et al. 2002, manuscript submitted to Mon. Wea. Rev.). Under favorable conditions, some MCC trajectories could reach São Paulo and potentially cause extreme precipitation events particularly from the Paraná valley to the high plains (Figueroedo and Scolar 1996; Silva Dias 1987).

6. Interannual variability of categories and ENSO

The discussion that follows has the purpose of elucidating some important aspects pointed out in Liebmann et al. (2001) concerning the correlation of warm SST episodes (El Niño) and the occurrence of extreme precipitation events in São Paulo. In the present study, the analysis is performed in the context of the annual distribution of SACZ categories. Figure 11 shows the number of events classified in each category and separated according to the SST episode defined with the same convention as adopted in Fig. 1. The distribution indicates that the intense-oceanic category was ~2.4 times more frequent during warm episodes, whereas the differences in other categories were negligible. Nogueás-Paegle and Mo (1997) and Hoerling and Kumar (2000), using rainfall and OLR anomalies, showed that an enhancement of precipitation in southeast Brazil extending toward the subtropical Atlantic (what has been subjectively defined as SACZ) is likely modulated by ENSO.

The present work suggests in addition to these observations and to Liebmann et al.’s (2001) results, that ENSO episodes modulate the fraction of extreme precipitation events when the SACZ is associated with enhanced convective activity over the western subtropical Atlantic. They are particularly relevant for the high plains and Mantiqueira regions. Conversely, extreme events observed along with enhanced convection in the SACZ with a higher extent over São Paulo, are unlikely modulated by ENSO. Weak SACZ activity does not seem to be modulated by ENSO, which is in agreement with Nogueás-Paegle and Mo (1997) and Hoerling and Kumar (2000).

Additional evidence of ENSO modulating the occurrence of extremes in conjunction with intense-oceanic patterns can be examined from the low- and high-level winds. Aceituno (1989) investigated relationships between anomalies of upper-air circulation in South America and the Southern Oscillation index (SOI) using radiosonde data. Although the Aceituno (1989) results cannot be generalized due to limitations in the number of episodes and spatial coverage, some important features of the 850-hPa circulation in the subtropics observed during negative SOI indexes from January to February of 1983 (see Aceituno’s Fig. 11) resemble the respective anomalies in the intense-oceanic category. Particularly relevant are the northwesterly anomalies of low-level winds (850 hPa) northwest of São Paulo, the southerly anomalies over Paraguay, and easterly anomalies near the coast of São Paulo (Fig. 8e). However, near the Caribbean islands and Central America coast, the low- and high-level westerly wind anomalies in Aceituno (1989) are not consistent with the easterlies observed in the intense-oceanic category (Figs. 8e and 8f). Differences in sampling and methodology may account for this disagreement.

The strengthening of the subtropical jet toward the western South Atlantic as indicated in Fig. 8e has been observed during ENSO episodes in 1983 and 1987, possibly as a consequence of the eastward migration of the equatorial Indo-Pacific convection (Grimm and Silva Dias 1995). According to them, this configuration of the subtropical jet favors the occurrence of anomalous precipitation in southeastern South America. Although these perturbations are stronger from austral winter to spring (Kousky and Ropelewski 1989), a similar rationale can be applied to explain the extension of the SACZ toward the ocean and therefore the intense-oceanic category and corresponding anomalies.

7. Conclusions

Daily extreme precipitation events in São Paulo, defined as those that produced 20% of the seasonal climatological total, were examined with the objective to elucidate the relationships with SACZ activity documented in the recent work of Liebmann et al. (2001). With this purpose, a more pragmatic definition of SACZ
was developed to be consistent with its observational characterization based on convective activity defined by cold cloudiness extent and maximum seasonal variance. In this definition, a threshold of OLR (i.e., OLR ≤ 200 W m⁻²) was used to identify regions of deep convective activity, whereas the mean SACZ spatial position and extent were determined according to the climatology. It is well known that daily OLR can be contaminated by the presence of cirrus clouds (e.g., Kiladis and Weickmann 1992). For this reason, in the present work the characterization of convection in the SACZ incorporated spatial and structural properties of OLR that evidenced its extent, intensity, spatial variability, and form. A multidimensional analysis of these OLR features was performed with factor analysis. The main advantage of this technique was that extreme events could be separated into categories according to the SACZ activity and the extent of low OLR toward to the Atlantic Ocean without any further subjective assumption. The interpretation of the relationships between SACZ activity and the environmental characteristics at the large-scale and the respective impacts on the regional occurrence of extreme precipitation in São Paulo are summarized in Fig. 12 and discussed in the following remarks.

- Approximately 65% of all extreme rainfall events occurred when convective activity in the SACZ was extensive and intense. However, both spatial configuration of SACZ and environmental properties associated with these events were distinct. Intense SACZ with deep convective activity extended toward the Atlantic Ocean (intense oceanic) was observed mostly north of São Paulo (30% of cases). A low-level anticyclonic anomaly over the western subtropical Atlantic Ocean was likely an important dynamical forcing for the enhancement of convection off the southeastern South America coast. There is evidence that this category of events was modulated by El Niño episodes. As a possible response to the eastward migration of the equatorial Pacific convection from its climatological position, the enhancement of the subtropical high-level jet over the Atlantic Ocean was

**Fig. 12.** Summary of SACZ characteristics in large and regional scales along with the occurrence of extreme precipitation events in São Paulo.
observed in this category. The spatial configuration of enhanced and suppressed convection is consistent with the presence of the seesaw in south-southeast South America in the summer as observed in Nogueś-Paegle and Mo (1997). On a regional scale, the intense-oceanic SACZ was especially important for the increase of extreme precipitation over the Mantiqueira and high plains.

- The complementary 35% of the extreme events associated with enhanced convection in the SACZ indicated intense convection in a large area of Brazil, with a significant extension over São Paulo but reduced toward the Atlantic Ocean (intense continental). Dynamical conditions inducing an enhancement of moisture advection from the Amazon to central-west Brazil and São Paulo may have played a role in the intensification of SACZ over a large part of the continent including southeast South America. The enhancement of the ITCZ activity over the equatorial Atlantic and near the northeastern coast of South America was linked with this category; these characteristics were not observed for the other categories. Associated with this category there is a significant increase in the number of extreme events throughout São Paulo, with the exception of the Mantiqueira region.

- The remaining 35% of total extreme events in São Paulo occurred when convective activity in the SACZ was reduced. Approximately 13% of these events were associated with an anomalous anticyclonic circulation near the coast of São Paulo. The dynamical configuration of low-level winds favored the extent of the narrow convection north of São Paulo toward the coast (weak oceanic), in a region where complex terrain is present. Consequently, there was an increase in extreme precipitation events in the coastal area related to this category.

- Another category of extreme events related to weak SACZ activity (~22% of the total events), was observed with a concentric area of continental deep convection restricted to southeastern Brazil (São Paulo, Minas Gerais, and Rio de Janeiro). The increase of northerly winds to the west of São Paulo and north of the Chaco low observed along with this category have been linked to the occurrence of MCCs and/or other organized mesoscale systems that eventually propagate toward São Paulo and cause extreme precipitation in that region.

In the present study, important aspects have been highlighted with respect to SACZ convective activity and the environmental conditions for the occurrence of extreme precipitation in São Paulo. Special attention was given to monitoring the SACZ extent and spatial form along with the anomalies of low- and high-level winds, and the evolution of El Niño episodes. Particular important dynamical features are as follows: 1) low-level wind anomalies over the western Atlantic, central Brazil, and São Paulo; 2) high-level wind anomalies over the subtropical Atlantic Ocean; 3) weakening of the Bolivia high; and 4) enhancement of convective activity in the ITCZ. These observations will not only improve forecasts of the SACZ but also provide additional elements to monitor extreme precipitation events in São Paulo.

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