Interannual Variability of Daily Extreme Precipitation Events in the State of São Paulo, Brazil

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ABSTRACT

The climatology and interannual variability of heavy, or ''extreme,'' precipitation events are studied, using station data from the state of São Paulo, Brazil. An extreme event is defined at each station when daily rainfall exceeds a certain percent of its seasonal or annual mean. It is found that these events occur mainly from November to March and that there is a distinct interannual variation in their number. The count of extreme events is not well correlated with mean precipitation. The relationship between extreme events and activity in the South Atlantic convergence zone (which, when active, is associated with increased precipitation) is therefore not obvious. From October to March, the interannual count of extreme events in the entire state is correlated positively with SST anomalies in the equatorial Pacific from near the date line to the west coast of South America. The interannual count at stations near the Atlantic coast from November to February is correlated positively with SST anomalies in the Atlantic Ocean near the latitude of São Paulo. In both cases the relationship between SST and mean precipitation is weak. The associations are confirmed with composites and rank correlations. The relationships described are apparent in the period 1976–77 to 1994–95. There is no correspondence evident between extreme events and SST if data beginning in 1948 are included in the analysis.

1. Introduction

Heavy precipitation events are among the most disruptive of atmospheric phenomena. They adversely affect urban populations because the infrastructure is often inadequate to accommodate flooding caused by these infrequently occurring events. In agricultural areas, crops can suffer damage from excess rainfall. On the other hand, because the distribution of precipitation is skewed toward large amounts, a few events can affect the seasonal total at an individual station, and therefore the adequacy of the fresh water supply (if it is locally derived) depends on the occurrence of such events (e.g., Gershunov and Barnett 1998).

Given the disproportionate influence of heavy, or ''extreme,'' precipitation events, the importance of understanding the underlying causes of the variability in their frequency of occurrence over a season or year becomes obvious. Previous studies of the variability in extreme events have been concerned with those occurring in the United States, and those in relation to the El Niño–Southern Oscillation (ENSO) phenomenon. Cayan et al. (1999) found that the probability of daily precipitation events exceeding the 90th percentile is more than double during the low phase of ENSO (associated with El Niño) compared to the high phase in most of the southwest. Gershunov and Barnett (1998) found a similar relationship in the southeast during winter (counting events exceeding the 75th percentile of days with rain).

The study described here is one of the interannual variability of daily extreme precipitation events in the state of Sao Paulo, Brazil. While the region studied was chosen because of the availability of data from a dense network of rain gauges, it is fortuitous that the region is interesting from a meteorological perspective as well.

The South Atlantic convergence zone (SACZ) is a

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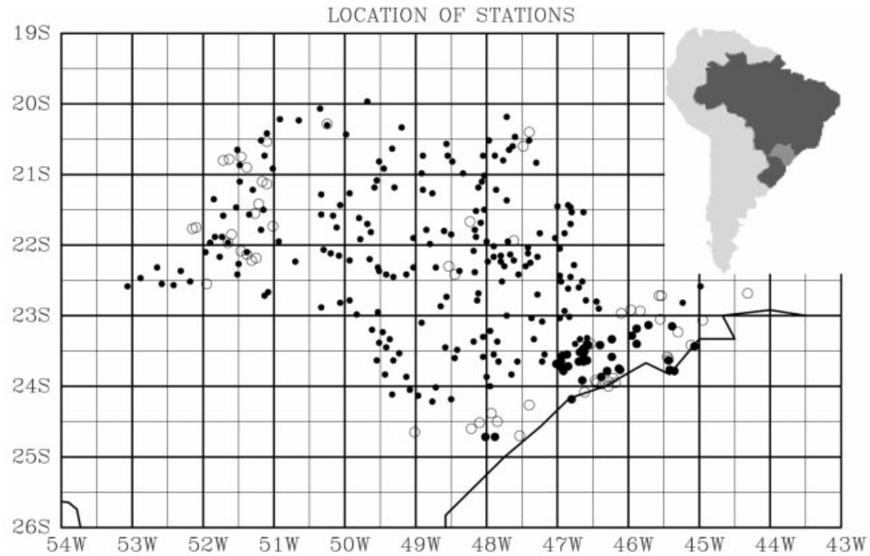

FIG. 1. Locations of the stations used in this study. Dots represent stations with data available for each year from 1976 to 1995. Large dots are those stations considered to be eastern São Paulo, small dots those in western São Paulo, and open circles additional stations used in constructing the gridded monthly mean data (see text). Inset shows area of study.

zone of enhanced convective activity that is most pronounced during Southern Hemisphere summer and is visible on maps of mean precipitation as a band that appears to emanate from the Amazon Basin and extend southeastward into the Atlantic, passing above the region considered to be ''southeast'' Brazil (e.g., Nogués-Paegle and Mo 1997). It seldom persists for more than 10 days (e.g., Figueroa et al. 1995; Nougés-Paegle and Mo 1997), and subseasonal variations have been shown to result from the propagation of midlatitude disturbances into the region (e.g., Liebmann et al. 1999). Variations of the SACZ also seem to be linked to the Madden–Julian oscillation (MJO; Madden and Julian 1994), which is a prominent intraseasonal variation of convection most active over the Indian and western Pacific Oceans (e.g., Casarin and Kousky 1986; Kiladis and Weickmann 1992; Nougés-Paegle and Mo 1997; Lenters and Cook 1999; Paegle et al. 2000). The explanation for the observation that the band of SACZ convection remains nearly fixed in space remains somewhat elusive, although it is likely to be related to the presence of Amazon convection (Kodama 1992; Figueroa et al. 1995).

The state of São Paulo is the southernmost in the region of southeast Brazil (which is distinct from ''southern'' Brazil). It is within the zone of most intense SACZ convection (e.g., Nougés-Paegle and Mo 1997). While an understanding of the variability of extreme events is important for any region, it is especially important for São Paulo state because of its large urban population. São Paulo is the most populous state in Brazil, and more than 90% of its 31.5 million inhabitants[1] live in an urban environment. The São Paulo metropolitan area, which is the largest in South America with about half the population of the state, is particularly adversely affected by extreme precipitation events. (The state of Rio de Janeiro, which is adjacent to São Paulo state along the coast, is the most densely populated in Brazil, with a density more than double that of São Paulo.)

2. Rainfall data

The rainfall data used in this study, which are believed to be of high quality, were provided by the Departamento de Águas e Energia Elétrica (DAEE) of São Paulo state. They consist of daily totals from 287 stations, whose locations are shown in Fig. 1. For these stations, the average record length is 40 yr from 1947 to 1995, which is the period of interest for this study, and of the available years, 1.2% are reported as missing. One hundred twenty-seven records contain some data for each year for that period. For the subset, an average of 0.7% are reported as missing. For a second subset of 234 stations with data from each year from 1976–95, an average of 0.55% are missing. In the following analysis, both gridded data and individual records are employed. The gridded dataset is monthly and is constructed by averaging all available records for a given month into

[1] Population data are from the 1991 census compiled by the Instituto Brasileiro de Geografia e Estatistica.

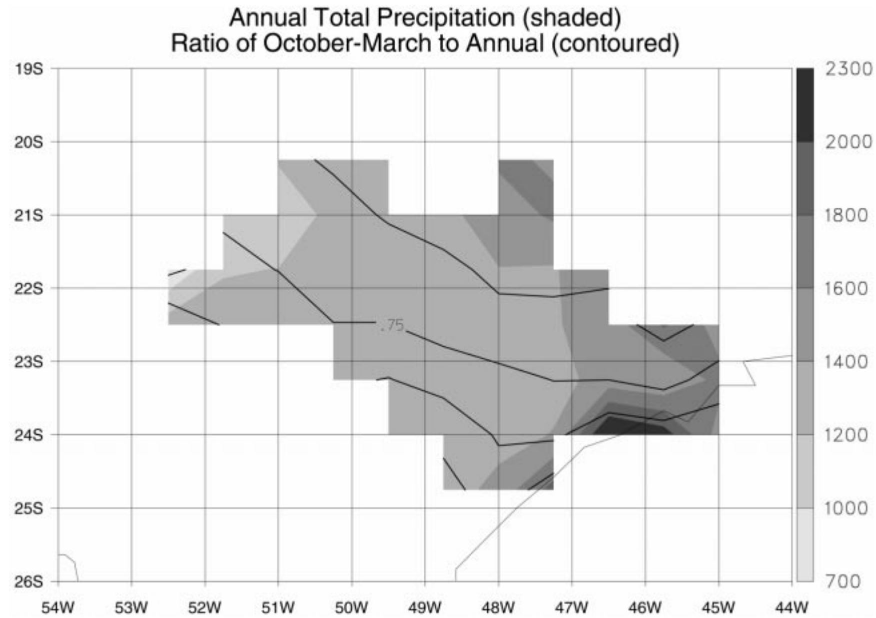

FIG. 2. Mean annual total precipitation in São Paulo state (shaded, values in mm) and ratio of Oct–Mar total to annual mean total (contoured, interval of 0.05).

0.75° grid boxes and multiplying by the number of days in the month. When individual records are used in the analysis, they are from the subsets of relatively complete data.

3. Characteristics of extreme events

Figure 2 shows the mean annual total precipitation in São Paulo. The largest amounts fall near the Atlantic coast, with a strong gradient in the vicinity of the coastal range. There are weaker gradients toward lesser amounts to the west, and toward higher amounts to the northeast. The rainiest month is January, with more than 200 mm at every grid box, while from May to September there is less than 100 mm everywhere (except a small area close to the coast that exceeds 100 mm in May and September). Throughout São Paulo state, October–March is the wet half of the year. The ratio of this 6-month climatology to the full year also is shown in Fig. 2. The ratio varies from near 0.6 to more than 0.8, with an increase in seasonality toward the north.

The most difficult aspect of this study lies in defining an extreme event. Since these occurrences are relatively rare with somewhat of a random component (a single storm may ''miss'' a station), it is desirable to group many stations within an area. Since each station has a different mean, however, what is considered extreme at one station may be a relatively common occurrence at another. For example, if an 80-mm event occurs several times a year at one location, the infrastructure has probably developed to mitigate its potential damage. On the other hand, if the same event occurs once in 5 yr, it well could result in disaster. Furthermore, a station with large annual total precipitation might experience drizzle nearly every day, but few extreme events.

The definition chosen for this study is simple but accounts for spatially varying climatologies while still allowing the benefits of summing the results from many stations. At each station the long-term annual (or seasonal) total is calculated for a given period, excluding missing values. Then, whenever the daily precipitation for a given period exceeds a given percent of the climatological mean for that period, it is considered as an event. The threshold percent is chosen to ensure that extreme events occur relatively rarely. Applying this definition to climatological annual means at each station in the entire state, there is a correlation between mean rainfall and the number of extreme events of −0.39 (for 4% extreme events), meaning that there are fewer events at stations at which precipitation is abundant. A regression shows that there is a 0.68% decrease in the number of extreme events for each centimeter increase in average total rainfall.

a. Annual variability of extreme events

Figure 3 shows the count of the average number of times per year that the daily precipitation exceeded 3%, 4%, and 5% of annual climatological total precipitation, summed over all stations, as a function of month, as well as the climatological number of station days with precipitation. All the curves exhibit a strong annual cycle, with maxima in January and minima in August. Using the 4% definition, there is about a 50% chance of an extreme event occurring in a given January at any

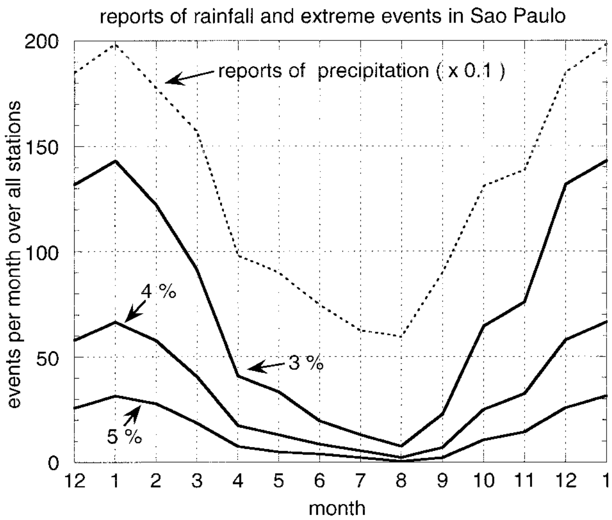

FIG. 3. Monthly climatology of extreme events (three lower curves) and reports of precipitation (upper dotted curve; count divided by 10) during period 1948–95. Extreme events are defined as the number of occurrences summed over the 127 stations in state of São Paulo when the daily precipitation equals or exceeds 3%, 4%, or 5% of the annual mean at each station.

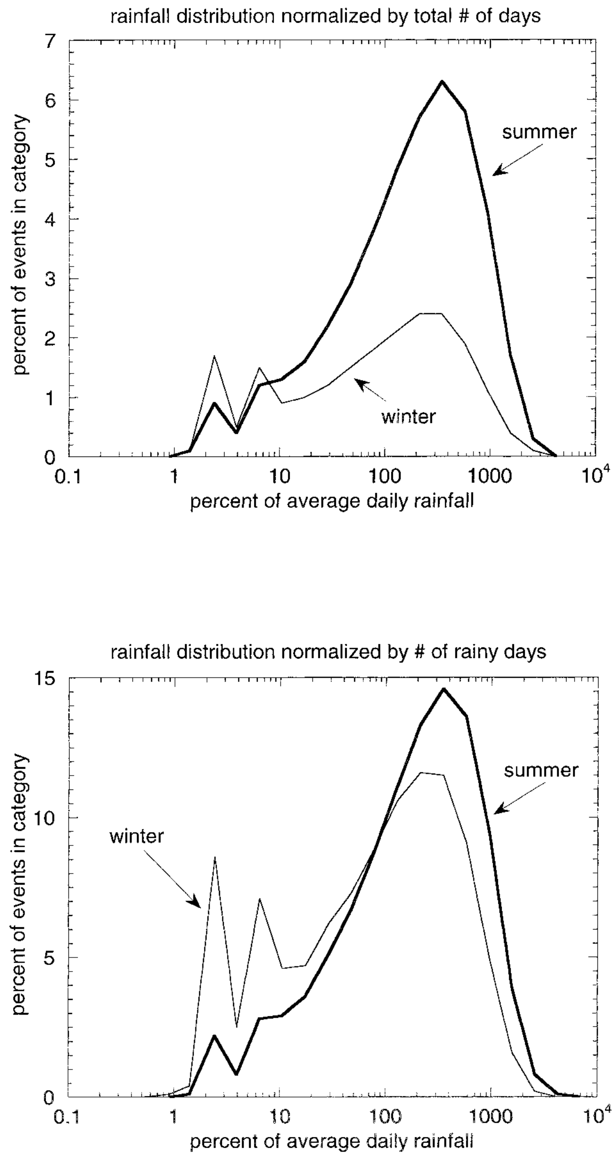

FIG. 4. Distribution of rainfall as a function of amount for summer (Oct–Mar; thick curve) and winter (Apr–Sep; thin curve). At each station value is computed as logarithm of the precipitation amount divided by its climatological daily average (annual total divided by 365) and then binned into an increment of 0.5. Ordinate represents sum over all stations normalized in (a) by total number of station days, and in (b) by number of station days with precipitation, and then both are converted to percent. Labels on abscissa are given as percent of daily mean.

station (67 events per month over 127 stations), and almost no chance of one occurring in August.

The distribution of amounts for all days with precipitation for summer (October–March) and winter (April–September) is shown in Fig. 4a. As one expects, during the relatively dry winter season the occurrences in most categories are less than during the convectively active summer, although there are actually more events in the lowest categories during winter. If the number of occurrences in each category is normalized by the number of days with precipitation, the difference between summer and winter is less pronounced toward the high end of the distribution, although now a shift between summer and winter in the most often occurring category becomes obvious. Even after normalizing by days with precipitation, there is still a large difference at the extreme positive tail of the distribution, with more events during summer. Thus, in addition to there being fewer days with precipitation during winter, there is a shift in the distribution toward smaller amounts.

b. Interannual variability of summertime extreme events

The number of events in which 8%, 10%, and 12% of the summer climatological total fell in 1 day for all stations is shown for each year in Fig. 5. A higher threshold was used for the summer analysis than for the entire year to ensure that only the largest events were included. On average there are 59, 21, and 9 events per season for all of the 127 stations using these thresholds. The correlation between the 10% and 12% categories is 0.86. The correlation between the 12% category and mean precipitation in the state for the same period (calculated by averaging the monthly gridded values together and multiplying by 6 months) is 0.39.

The average distribution of rainfall for the six summers with the largest number of 10% extreme events, the fewest number, and for all years is shown in Fig. 6a. If one were considering 10% extreme events, they would appear as those events greater than 1820% of average daily rainfall in this figure. During summers

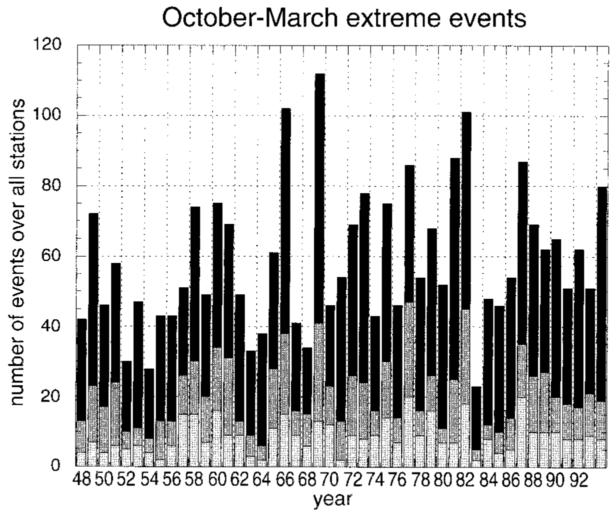

FIG. 5. Number of daily precipitation events in state of São Paulo from Oct to Mar for each year that equals or exceeds 8%, 10%, and 12% of climatological total for same period at each station, summed over all stations.

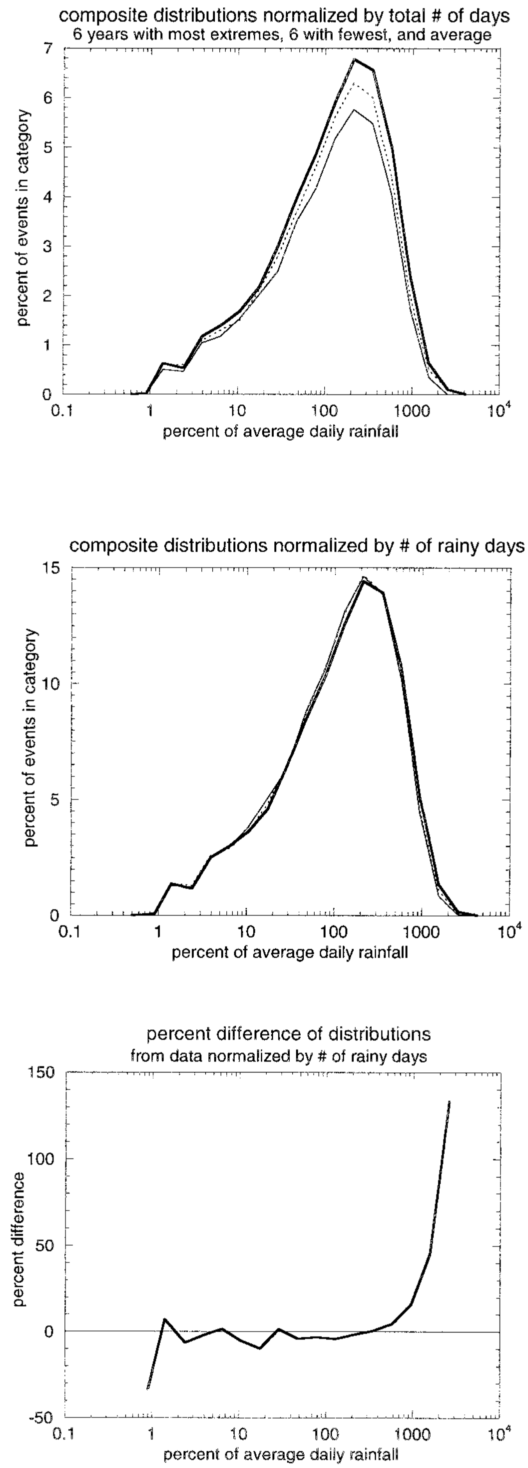

FIG. 6. (a) and (b) As in Fig. 4 except distributions are for Oct–Mar and curves are composite of all years (dotted), composite of six seasons with most (thick) and fewest (thin) events (defined as daily rainfall that exceeds 10% of Oct–Mar climatology). (c) Percent difference of curves (composite of highest minus composite of fewest divided by average) in (b).

with a large number of extreme events there are more events in each category than during years with few events. It is primarily the amplitude and not the shape of the distributions, however, that appear to depend on the number of extreme events. This is illustrated further in Fig. 6b, which shows the same composite distributions, but normalized by the number of days with precipitation. Now the distributions appear to be nearly identical, which is in distinct contrast to the difference between summer and winter (Fig. 4b).

The similarity of the distributions for composites of summers with many and few extreme events suggests that an important parameter is the occurrence of measurable rainfall. It appears that over many events the relative frequency of events in each category is nearly constant. By this logic, the number of extreme events should increase simply because there are more days with rainfall during a given season (and therefore more events in each category). On the other hand, if one plots the percent difference between the high and low composite curves of Fig. 6b, there is a large percent difference at the upper tail of the distribution (Fig. 6c), although in absolute terms all the differences are quite small. There is a small decrease in the relative occurrence in most of the rest of the distribution, which is required, as the integral of the absolute difference must be zero. While in some sense this result may be ‘‘built-in’’ (i.e., we are compositing about the years with the highest and lowest number of extreme events), if the occurrence of extreme events were simply proportional to the number of days with precipitation, which is a close approximation for the rest of the spectrum, the difference would be near zero in all bins.

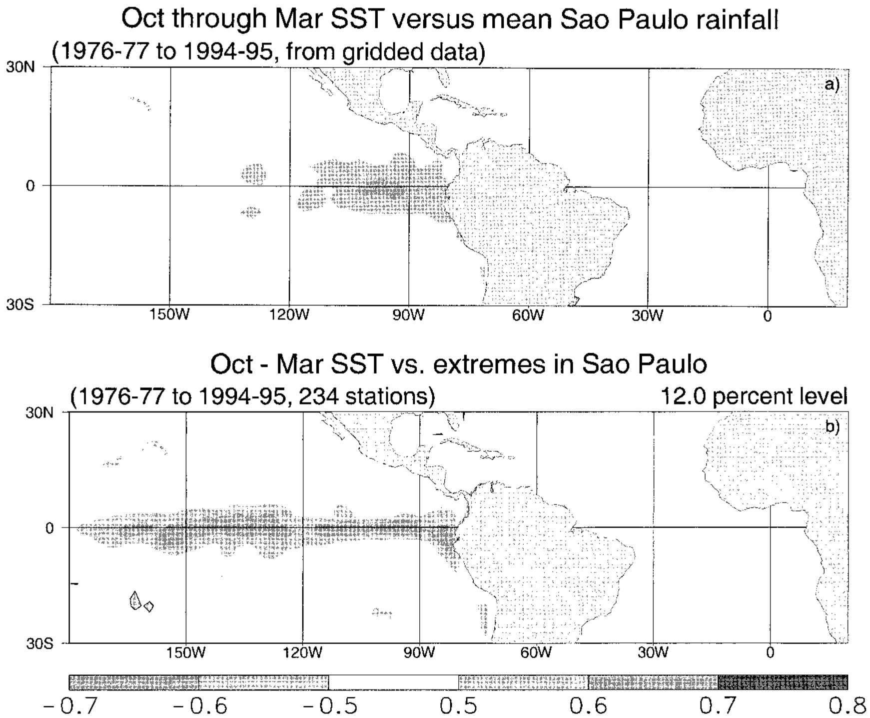

FIG. 7. (a) Correlation between mean rainfall in the state of São Paulo rainfall (calculated by summing gridded monthly rainfall totals over each grid box and from Oct to Mar and dividing by the number of grid boxes) and SST for the same period. (b) Correlation between number of extreme events in 12% category (see text for explanation) and SST for the same period as in a. Shading starts at ±0.5 with an interval of 0.1. Negative correlations are both contoured and shaded. Calculations are for the period 1976–77 to 1994–95.

c. Relationships between mean rainfall, extreme events, and sea surface temperature

It is well established that anomalies in sea surface temperature (SST), particularly those in the central and eastern tropical Pacific Ocean associated with ENSO, are associated with atmospheric circulation anomalies in both the Tropics and midlatitudes. When the location of the warmest tropical water shifts, the position of convection shifts as well, which alters the pattern of latent heating in the Tropics, resulting in anomalies in the wave trains that propagate into midlatitudes (e.g., Horel and Wallace 1981; Hoskins and Karoly 1981; Ambrizzi and Hoskins 1997). Since midlatitude rainfall anomalies are related to the anomalous position of the ridges and troughs, there is an expectation that in some places seasonal precipitation amounts should vary depending on the state of ENSO.

Several studies have indeed shown consistent regional signals in rainfall in South America associated with ENSO during southern summer. In the north, there is a deficit during the negative (warm) phase of ENSO, except near the equatorial west coast (e.g., Ropelewski and Halpert 1987; Aceituno 1988; Rogers 1988; Kiladis and Diaz 1989; Rao and Hada 1990).

In southeast South America, the results are somewhat more ambiguous, in part because most studies have had only a few stations available for analysis (Grimm et al. 1998). Rogers (1988) showed a general excess of rainfall in summer during the low phase of ENSO, but in the vicinity of São Paulo the relationships change sign from a surplus to a deficit of rainfall from the beginning to the end of the 6-month October–March period. Aceituno (1988) observed a negative correlation between an index of the Southern Oscillation and rainfall in the Paraná River basin. More recently, and with many more stations than previously had been used, Pisciottano et al. (1994) found above median precipitation in Uruguay during El Niño years (mostly from November to January and the following March to July). Diaz et al. (1998) confirmed these results (expanded to include southern Brazil) and also showed that warm SST in the southern Atlantic to be associated with increased rainfall during approximately the same seasons. Grimm et al. (2000), using data from most of southern South America, found a broadly consistent result when harmonics of monthly percentile precipitation were fit to 2-yr El Niño and La Niña cycles. They found no large signal in the state of São Paulo.

Figure 7a shows the simultaneous correlation between total summer rainfall, calculated as an average over the gridded fields whose domain is shown in Fig. 2, and average SST (from NCEP–NCAR reanalysis fields) for

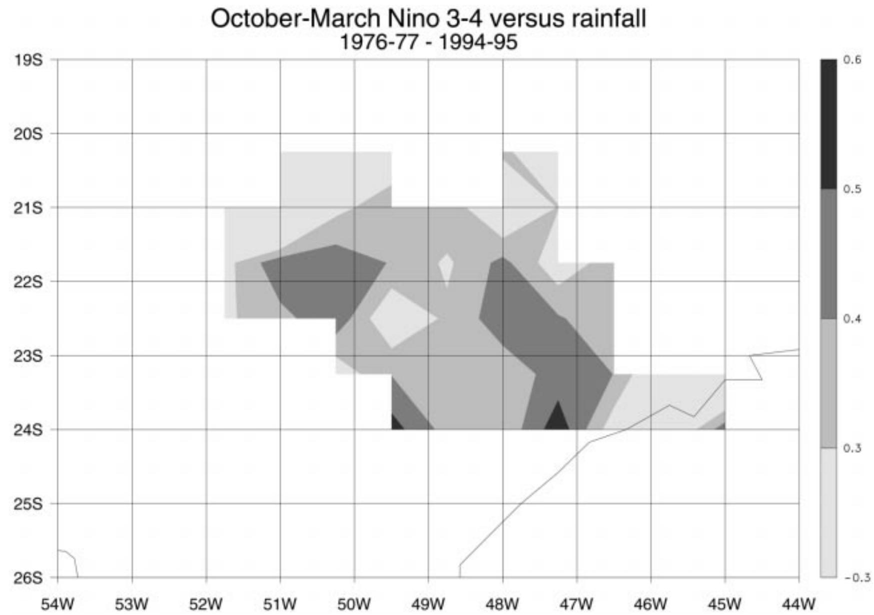

FIG. 8. Simultaneous correlation between Niño-3.4 SST index (described in text) and Oct–Mar rainfall at each grid box. Areas with correlations between 0.3 and −0.3 are lightly shaded, with darker shading beginning at 0.3 with an interval of 0.1.

the same period. The results shown in this section are computed for the years 1976–77 to 1994–95. In almost all examples described here, correlations are dramatically larger using this subset than they are if the entire record (beginning in 1948) is used. There is evidence that El Niño impacts over the Americas have been significantly greater since 1976 relative to periods before (M. P. Hoerling 1999, personal communication).

The correlations between the index of statewide rainfall and SST are small everywhere except near the west equatorial coast of South America. On the other hand, when SST is correlated with the number of extreme events at the 12% level (Fig. 7b) there exist relatively large correlations in the western Indian and eastern Pacific Oceans. The null hypothesis is rejected at the 95% level using a two-sided *t* test for a correlation of about 0.46, assuming each year of the 19-yr subset to be independent. The area of large correlation in the eastern Pacific is clearly associated with ENSO. The correlations become larger as the threshold definition of an extreme event is increased (not shown). While one must be extremely cautious in interpreting these results because mean rainfall and the count of extreme events (and SST) is unlikely to follow a Gaussian distribution (see section 3d), this figure does suggest that there is an important difference between indices of mean rainfall and the number of extreme events.

The simultaneous correlations between the summer average SST anomaly in the Niño-3.4 region (defined as the area from 5°N to 5°S, 170° to 120°W) and average

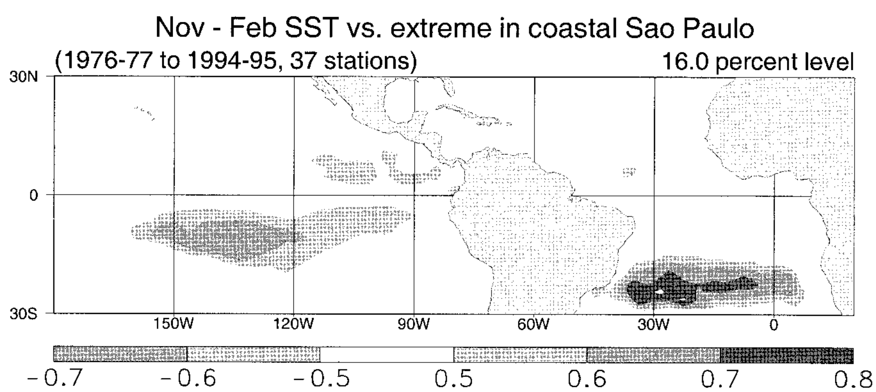

FIG. 9. As in Fig. 7b except that simultaneous correlation is from Nov to Feb and stations from which extreme events are determined are in coastal São Paulo (defined as those 37 stations within a circle with radius of 10° whose center is at 32.5°S, 42.5°W) and events at 16% level are counted.

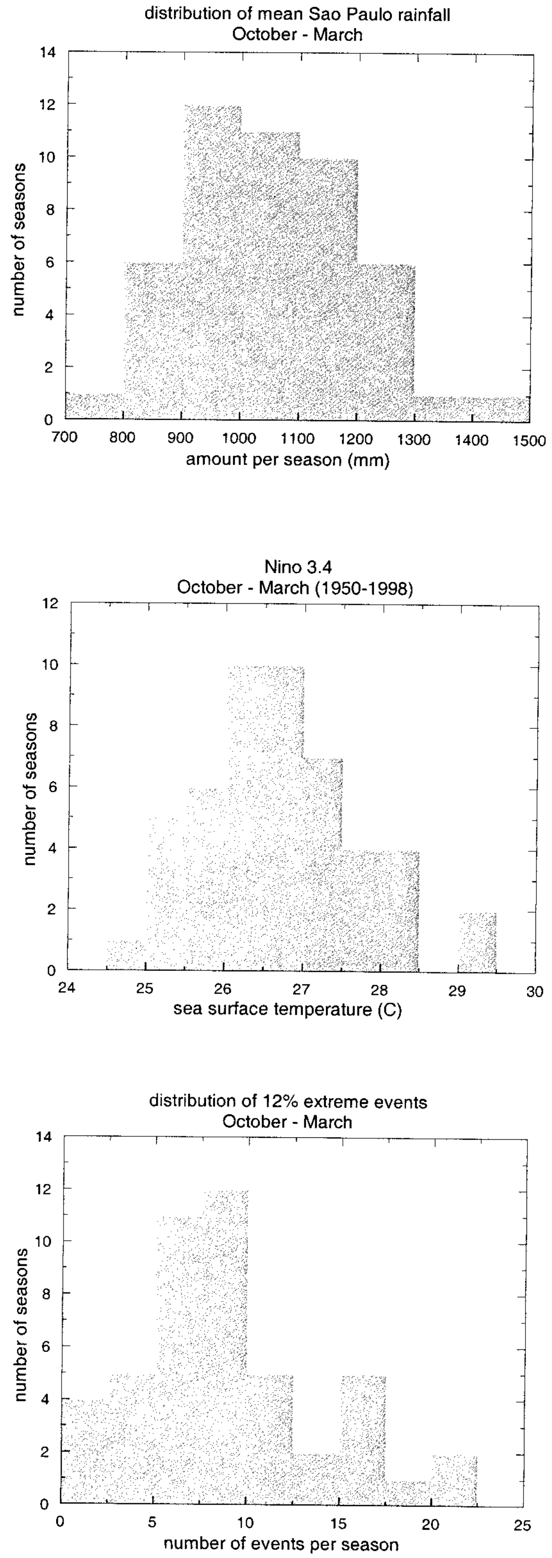

FIG. 10. The interannual distribution from Oct to Mar of (a) mean rainfall in state of São Paulo, (b) the Niño-3.4 index, and (c) 12% extreme events.

rainfall in each of the grid boxes within São Paulo are shown in Fig. 8. As expected, correlations are weak throughout the state, although generally positive. When the December–February season is used, values increase slightly in the central part of the state (not shown). Correlations are weak throughout the state an index of Niño-3 (5°N–5°S, 150°–90°W) is substituted. It is not appropriate to do the same calculation replacing mean rainfall with the count of extreme events within each grid box because in many years there are no extreme events in a given grid box; it is only by summing over many stations that one is assured of having several events in each year. If extreme events are summed by region, however, most of the Pacific SST signal is coming from stations in eastern São Paulo state. If extreme events in the far east (whose locations are shown in Fig. 1) are correlated with SST (not shown), the result is similar to that when all stations in the state are used (Fig. 7b). On the other hand, there is little signal using stations in the western part of the state (not shown). It is conceivable that the large-scale circulation patterns that favor synoptic and mesoscale rainfall in the eastern part of the state are different from the rain-producing pattern in the rest of the state, as the far east is characterized by steep, southeast-facing orography.

An interesting relationship is evident if extreme events in the eastern part of the state from November to February are simultaneously correlated with SST (Fig. 9). As the threshold is increased, an area of high correlation emerges from the south Atlantic, centered slightly north of São Paulo state, whose pattern is quite similar to that associated with increased mean precipitation farther south (Diaz et al. 1998). There are no statistically relevant correlations when an index of SST from 20° to 28°S, 15° to 35°W (approximating the area of largest correlation in the Atlantic) is correlated simultaneously with gridded precipitation for the same period. If the coastal station extreme count is correlated with SST that leads by one 4-month period (not shown), however, the correlation is relatively large in the East Pacific (slightly south of the equator), but there is little precursor in the Atlantic.

d. Distributions of rainfall and problems caused by non-Gaussian distributions

Although linear correlations are both revealing and easy to implement, for this analysis technique to be strictly valid, variables should follow Gaussian distributions. If they do not, the results may be misleading. The interannual distribution of summer rainfall (obtained by averaging over all grid boxes) is shown in Fig. 10a. There appears to be a slight positive skew (a tail to large values), comparable to that of Niño 3.4 (Fig. 10b). The distribution of extreme events (Fig. 10c), however, shows a relatively large positive skew, which clearly departs from a Gaussian distribution.

To address the possibility that the correlations be-

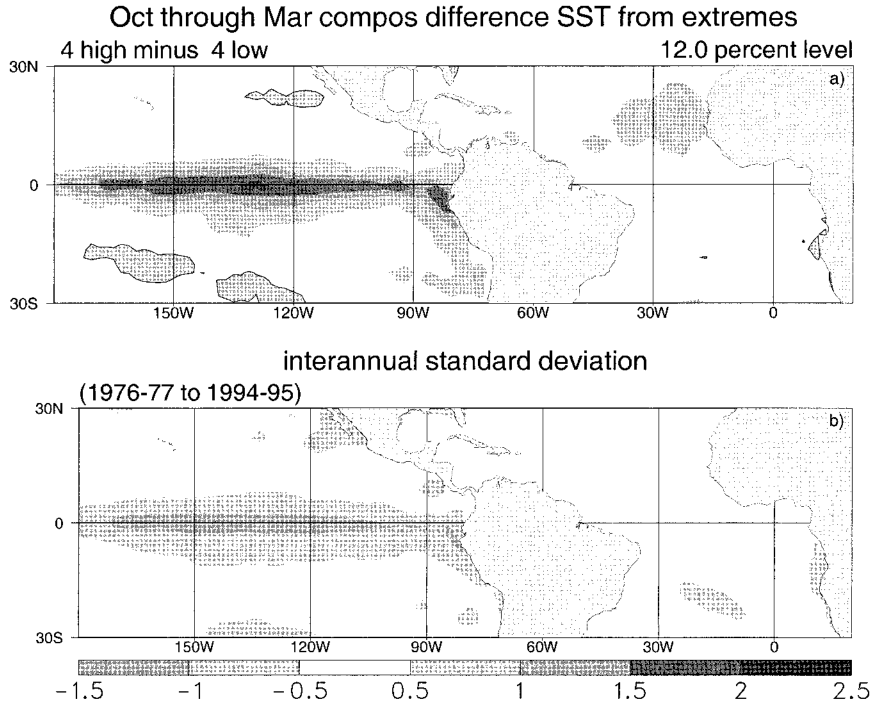

FIG. 11. (a) Composite difference of SST average for 4 yr with highest number minus SST average for 4 yr with lowest number of 12% extreme events for Oct–Mar season for 1976–77 through 1994–95. (b) Interannual standard deviation of Oct–Mar average SST for same years. Shading is in Celsius. Negative values in (a) are both contoured and shaded.

tween SST and the number of extreme events are misleading because of the non-Gaussian distribution of extreme events, composite SST differences for the four summers with the largest number of extreme events, minus the 4 summers with the fewest, are shown in Fig. 11a (corresponding to Fig. 7b). The difference is seen to be larger than the interannual standard deviation for the same months (Fig. 11b). The composite SST differences based on coastal extremes from November to February (Fig. 12, corresponding to Fig. 9) are larger than the standard deviations (not shown) in both the Pacific and the South Atlantic.

The rank correlation, in which the rankings of each field are correlated, is another method designed to establish relationships between fields that may not be normally distributed. Figure 13 shows the rank correlation corresponding to Fig. 7. There is no signal when mean precipitation is correlated with SST (Fig. 13a), but there is an association with extreme events (Fig. 13b). When coastal extremes from November to February are rank correlated with simultaneous SST (not shown), there is a strong Atlantic signal that matches well with its counterpart, shown in Fig. 9.

4. Summary and conclusions

The purpose of the research reported here was to examine the statistics of occurrence of large, rare, daily precipitation events in the state of São Paulo, Brazil, which can cause property destruction and loss of life. An extreme event is counted at each station for each day on which rainfall exceeds a given percent of the seasonal (or annual) total at that station. The threshold percent is adjusted to ensure that the events in question occur only infrequently. The counts are then summed over all stations of interest for a given period. This method was developed to address problems that can arise by using a single station or by counting events as those above a certain percentile.

The overwhelming majority of extreme events occur in the months from October to March, defined as summer. Composite distributions of all rainfall events for summer and winter reveal that during summer there are more days with rainfall and that the mean rain event is larger than in winter. If composite distributions are compared for summers with high and low counts of extreme events, there are more events in each category in summers with a large number of extreme events. When the distributions are normalized by the number of days with rainfall, however, they appear quite similar, except that the high end is still characterized by more events (at the expense of near-average events) during summers with a large number of extreme events. Thus the conclusion is that it is more than a simple count of the number of days with rainfall that determines the distribution, and therefore the number of extreme events in a given year, even though there is a weak positive re-

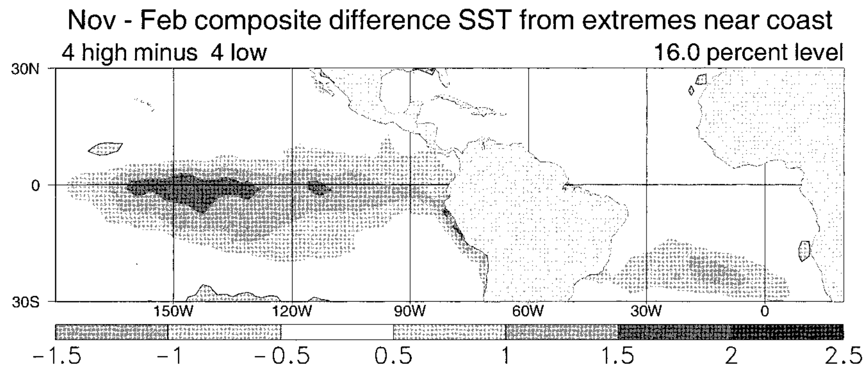

FIG. 12. As in Fig. 11 except for Nov–Feb and threshold for extreme events is 16%.

lationship between the mean precipitation and the number of extreme events.

Mean rainfall in the vicinity of São Paulo state during summer is thought to be increased by the presence of an active SACZ (e.g., Casarin and Kousky 1986; Nogués-Paegle and Mo 1997). The relationship between mean rainfall associated with SACZ activity and extreme events, however, is not obvious. For example, while an intense SACZ may spawn extreme events, it may be short-lived. More modest, but long-lasting SACZ activity, while not intense enough to produce extreme events, may result in as much rainfall as the intense SACZ, but spread over time. We speculate that, consistent with synoptic experience, extreme precipitation events are related to intense squall lines.

There is a positive correlation between the number of extreme events in the entire state and SST anomalies in the central and eastern Pacific. There does not appear to be a strong correlation between SST and total summer precipitation. Most of the SST-extreme event relationship seems to come from stations in the eastern part of the state. There is also a relationship of the same sign from November to February between extremes in the eastern part of the state and SSTs in both the eastern Pacific and the South Atlantic, but again, no relationship between SST and total rainfall. These correlations are confirmed with composites and rank correlations, necessary since the distribution of extreme events (and mean precipitation) is not normal. The relationships between extreme events and SST are apparent in the period

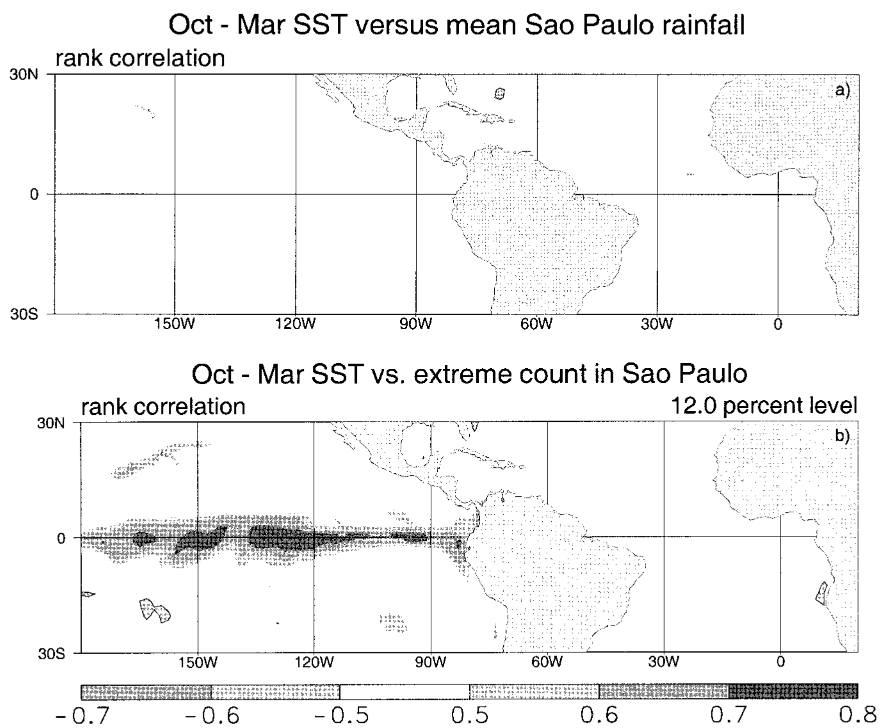

FIG. 13. As in Fig. 7 except using rank correlation (see text for explanation).

1976–77 to 1994–95, but not when data beginning in 1948 are included in the analysis.

While individual extreme events undoubtedly are important for the damage that they can incur, it is likely that there are relationships in time and space between extreme events. These were not examined in the present study, but may be part of future work. Likewise, the idea that extreme events are associated with squall lines needs to be examined critically as well.

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