Trends, spectral characteristics, and rainfall relationships of low-latitude sea surface temperatures at different longitudes

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Abstract. The sea surface temperature (SST) data for low latitudes in the Pacific, Atlantic, and Indian Oceans for 1950-1996 (47 years) showed different seasonal variation patterns at different longitudes. When the seasonal patterns were subtracted from the monthly values, the deseasoned residuals showed considerable anomalies (interannual variability). In the Pacific the main features were the El Niño events. In the Atlantic, North and South Atlantic SST showed dissimilar anomalies, and these did not have any fixed lag or lead relationships with the Pacific events. The same was true for the low-latitude Indian Ocean SST. The correlation of Pacific SST with Atlantic or Indian Oceans' SST was less than -0.65, yielding a common variance (square of the correlation) of less than -40% Thus, whereas SST anomalies might have some common origin, the manifestation of SST anomalies at different longitudes was erratic, with no preference for any longitude to start with, nor any definite sequence of occurrence in the Pacific relative to the Atlantic or Indian Oceans. A spectral analysis showed that all regions had quasi-biennial, quasi-triennial, and higher periodicities, but the exact values of these periodicities differed significantly at different longitudes. All parameters had long-term trends. These were mostly nonuniform, almost negligible in the first half (1950-1973) and mostly upward in the second half (1973-1996), indicating warming in recent decades, which is also reflected in decreases in snow cover area in the Northern Hemisphere. Rainfalls in various regions are considerably influenced by local SST regimes. For northeast Brazil, Atlantic SST influence is overpowering and often operates independently of the Pacific SST (El Niños). Hence the emphasis given in mass media (press, radio, and television) to the role of El Niño events only in influencing the rainfalls may turn out to be misleading, as seems to have happened for the 1997 El Niño. This El Niño started in early 1997 but did not have any significant influence on rainfall in northeast Brazil and India. It continued strongly in 1998, causing a severe drought in northeast Brazil but no drought in India.

1. Introduction

The characteristics of tropical sea surface temperature are not the same at all longitudes. For example, the amplitude of the interannual climatic variability with respect to the seasonal signal differs widely between the tropical Pacific and Atlantic Oceans [Streiten, 1981; Servain, 1991]. Interannual sea surface temperature (SST) perturbations are strongest in the tropical Pacific Ocean, particularly during El Niño-Southern Oscillation (ENSO) episodes, while the annual cycle dominates in the Atlantic [Merle et al., 1980; Hastenrath, 1984], mainly because of seasonal upwelling in the eastern part of the basin. For the tropical Atlantic, empirical orthogonal function (EOF) analyses [e.g., Weare, 1977; Hastenrath, 1978; Lough, 1986; Servain and Legler, 1986] suggest two main modes of SST variability. The first mode represents a warming or cooling trend in the whole basin, and the amplitudes indicate a long-term temperature trend. The second mode exhibits an asymmetrical structure (dipole) about the equator. Variations of this thermal dipole are associated with anomalous meridional displacements of the kinematic axis separating Northern and Southern Hemisphere trades [Lamb, 1978b], a more southward (northward) position of the axis being associated with warmer (cooler) conditions in the southern part of the basin and cooler (warmer) conditions in the northern part. The Atlantic SST dipole is reported to be related to the tropospheric circulations over the Northern Hemisphere [Déqué and Servain, 1989]. Large-scale Atlantic anomalies in association with ENSO have been reported by Hastenrath and Heller [1977], Covey and Hastenrath [1978], Hastenrath and Wu [1982], Hastenrath et al. [1987], and Wolter [1987]. Sperber and Hameed [1993] suggest that the Walker circulation and the tropical Atlantic circulation interact on timescales of ~12, 9, 6, 3.6, and 2.1 years. Hastenrath and Kaczmarsczyk [1981] report that the sea level pressure (SLP) in the eastern equatorial Pacific and SLP and SST in the Atlantic show large variance in the long end of the spectrum. These authors also report that the SST in the El Niño region off the Ecuador-Peru coast differs from other parts of the world oceans in that the variance is concentrated at 2-8 and ~15 years, rather than at the long end of the spectrum. Nicholson and Nyenzi [1990] mention that the dominant timescale in the tropical Atlantic and western Indian Oceans is ~4-6 years, the same as for the Southern Oscillation. Cadet [1985] and Yasunari [1987a, b] find ENSO signals in SSTs in the Indian Ocean. Meehl [1987] identified a biennial signal in the coupled ocean-atmosphere system in the tropical Indian and Pacific regions. Meehl [1993] explored further the role of oceans and suggested that the changes in upper ocean heat content contribute to the persistence of sea surface temperature anomalies important to the biennial mechanism, that both the Indian and Pacific Oceans are actively involved in ENSO, and that ENSO could be an amplification of the biennial cycle. Mehta and Delworth [1995] obtained quasi-decadal oscillations...
in numerical ocean-atmosphere models for the Atlantic Ocean, while Mehta and Lau [1997] explored the influence of solar irradiance on the Indian monsoon-ENSO relationship at decadal-multidecadal timescales. Mehta [1998] studied the variability of the tropical ocean surface temperatures at decadal-multidecadal timescales in the Atlantic Ocean, while Zhang et al. [1998] studied the modes of interannual and interdecadal variability of Pacific SST. For the region off NE Australia, Lough [1992] reported that the SST anomalies in the northeastern part of that region varied in a manner opposite to that of the rest of the region, more like the central Pacific rather than the west Pacific. Earlier, Streten [1983] had mentioned that SST anomalies in the eastern Pacific were sometimes opposite to those of the western Pacific (Australasia). Recently, Nicholson [1997] examined the time-space evolution of the ENSO signals in the tropical Atlantic and western Indian Oceans, using harmonic analysis similar to that used earlier by Ropelewski and Halpert [1987, 1989], and reported that on the average, warming begins along the southeastern Atlantic coast early in year 0 (year of maximum warming in the Pacific) and some months later begins elsewhere in the Atlantic and Indian Oceans. However, some ENSO episodes were found to be less effective than others, and the strongest 1982-1983 episode showed Atlantic and Indian Oceans’ SST pattern developments different from those for the average of earlier events.

In this paper the characteristics of tropical SST in the Pacific, Atlantic, and Indian Oceans are reexamined and compared for a longer, common period of ~45 years (1950-1997). Spectral characteristics are studied by an accurate maximum entropy method. It is shown that the teleconnection between Pacific and Atlantic SST is rather loose, and during El Niño events (Pacific SST anomaly positive), Atlantic SST can have a variety of patterns, often different for the North and South Atlantic. The role of SSTs in rainfall extremes in some regions is examined. In particular, northeast Brazil rainfall is shown to be greatly influenced by Atlantic parameters, to the extent that in some El Niño years, the effect of El Niños (droughts) could even get neutralized by Atlantic effects, resulting in normal or slightly excess rainfall in northeast Brazil. The effects of the recent 1997-1998 El Niño on rainfall in some parts of the globe, particularly for northeast Brazil, are discussed.

2. Data

Data were obtained from the web sites for the archives of the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP), Washington D.C., (at http://mic.fb4.noaa.gov/data/cddb/cddb/sstoi.indices) and from NOAA-Cooperative Institute for Research in Environmental Science’s (CIRES) Climate Diagnostics Center, University of Colorado, Boulder (at http://www.cpc.ncep.noaa.gov/data/cddb). Locations of the various parameters used are given in Table 1. Each cross represents 12° of longitude. For the Indian Ocean the Reynolds SST data were used. Besides SST at different longitudes, trade winds at 850 hPa, outgoing long wave radiation (OLWR) near the equator, Eurasian snow cover area, and Southern Oscillation Index represented by Tahiti minus Darwin pressure difference (T-D) were also examined.

3. Characteristics and correlations

Figure 1a shows a plot of monthly values for a sample period of 10 years (1950-1959). As can be seen, the most prominent feature is the seasonal variation. The average seasonal variation for the whole period (1950-1996) is shown in Figure 1b. The North Atlantic has a temperature maximum in September-October, while the South Atlantic has a minimum near those months. However, the two plots are not exactly opposite nor are their amplitudes equal (range is 2.5°C in the North Atlantic and 4.0°C in the South Atlantic). Hence their average, (N+S)/2, representing the low-latitude SST still has a seasonal variation, qualitatively like the South Atlantic (SST maximum in April-May and SST minimum in August-September). The tropical SST representing the average for all longitudes also has a similar variation, probably because, apart from the influence of South Atlantic, the El Niño regions 1+2 and 3 and the Indian Ocean also have a similar seasonal variation. Incidentally, the seasonal

### Table 1. Details of Regions for Which Parameters Were Used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Latitude, deg</th>
<th>Longitude, deg</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>180°-120°W</td>
<td>120°-60°W</td>
</tr>
<tr>
<td>SST Puerto Chicama</td>
<td>8°S</td>
<td>x</td>
</tr>
<tr>
<td>SST El Niño 1+2</td>
<td>0°-10° S</td>
<td>xx</td>
</tr>
<tr>
<td>SST El Niño 3</td>
<td>5°N-5°S</td>
<td>xxx</td>
</tr>
<tr>
<td>SST El Niño 4</td>
<td>5°N-5°S</td>
<td>xx</td>
</tr>
<tr>
<td>SST North Atlantic</td>
<td>5°N-20°N</td>
<td></td>
</tr>
<tr>
<td>SST South Atlantic</td>
<td>0°-20°S</td>
<td></td>
</tr>
<tr>
<td>SST(N+S)/2 Atlantic</td>
<td>20°N-20°S</td>
<td>xxx</td>
</tr>
<tr>
<td>SST (N-S) Atlantic</td>
<td>20°N-20°S</td>
<td>xxx</td>
</tr>
<tr>
<td>SST Indian Ocean</td>
<td>5°N-5°S</td>
<td></td>
</tr>
<tr>
<td>SST Tropical</td>
<td>10°N-10°S</td>
<td>xxx</td>
</tr>
<tr>
<td>SLP at Tahiti</td>
<td>18°S</td>
<td>x</td>
</tr>
<tr>
<td>SLP at Darwin</td>
<td>12°S</td>
<td>x</td>
</tr>
<tr>
<td>Eurasian snow cover</td>
<td>−40°N</td>
<td>xxx</td>
</tr>
<tr>
<td>850 hPa trades</td>
<td>5°N-5°S</td>
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The crosses indicate the longitude range involved (each cross equals 12° longitude) and five crosses cover the entire 60° longitude range given at the top of each column. SST, sea surface temperature; SLP, sea level pressure; OLWR, outgoing long wave radiation.
In the middle part of Figure 1c the El Niño SSTs show prominent maxima in 1951, 1953 and 1958. These are well-known El Niño events, very prominent near the Ecuador-Peru coast (Puerto Chicama; note the different vertical scale). The El Niño 1+2 and SST Puerto Chicama match very well, as expected (roughly the same region), but the Puerto Chicama amplitudes are larger. The SST anomaly magnitudes are lesser for El Niño 3 and still lesser for El Niño 4, indicating that either the effects fizzle out away from the South American coast or are spread more uniformly over vast areas, or both.

The North Atlantic SST also has maxima in these 10 years but not coinciding with the El Niños. In 1955-56, North Atlantic SST had maxima, but the El Niño regions had minima (La Niñas).

Whenever El Niño regions had SST maxima, Tahiti minus Darwin pressure difference T-D had prominent minima, indicating an anticorrelation, though sometimes there were phase shifts [Deser and Wallace, 1987].

The Indian Ocean anomalies are roughly similar to the El Niño region anomalies (at least for this interval) but differ in details. The same is true for tropical SST (average for all longitudes). In particular, the 1955-1956 maxima in North Atlantic SST are not reflected in the Indian Ocean SST or in the tropical SST.

Servain [1991] discussed the relationship between Atlantic SST and ENSO phenomena. For 1964-1990, Servain summarized the results as follows: Relatively cold anomalies are present in the south tropical Atlantic a few months before the peak of an El Niño event. Immediately following this peak, strong, warm SST anomalies are observed in the north tropical Atlantic, and a few months later, the whole basin is finally warmer than normal. To check this pattern, we performed a cross-correlation analysis for the monthly values in Figure 1c (1950-1959), using El Niño 1+2 as the primary reference parameter. The results are shown in Figure 2. Plot 1 shows that SST at Puerto Chicama has a very good correlation (+0.82±0.03) with SST El Niño 1+2, with no lag. This is easily understandable, as SST El Niño 1+2 includes SST Puerto Chicama. Plot 2 shows that SST El Niño 3 has the same
correlation (+0.82±0.03) but with a lag of 1 month; that is, the SST El Niño 3 values reach a maximum 1 month later. Plot 3 shows that SST El Niño 4 has a broad maximum, but the maximum correlation (+0.72±0.04) is at a lag of 5 months. Plot 4 for tropical SST (average of all longitudes) shows a correlation (+0.78±0.04), with a lag of 1 month. Plot 5 for T-D shows a negative correlation (-0.60±0.06) but at a lag of 2 months, indicating the phase shifts mentioned by Deser and Wallace [1987]. Thus the ENSO relations in the low-latitude Pacific are good, with lags within a few months. On the other hand, plot 6 for North Atlantic SST shows poor correlations with a maximum value of +0.39±0.08 at a lag of 3 or more months, that is, warming of the North Atlantic a few months after the El Niño. Plot 7 for South Atlantic SST shows very poor correlations (+0.16±0.09), with a lag of 1 month. Thus the patterns mentioned by Servain [1991] are seen poorly. On the other hand, plot 8 for Atlantic SST (N-S)/2, that is, the average for tropical Atlantic SST, shows a better correlation (+0.46±0.07) at a lag of 3 months. In contrast, plot 9 for Atlantic SST (N-S) dipole shows a poor correlation (+0.29±0.08) at a lag of 10 months. Finally, plot 10 for Indian Ocean SST shows a reasonably good maximum correlation (0.61±0.06) but at a lag of 7 months. Servain mentioned that the patterns were most pronounced for extreme ENSO events. This aspect is examined in section 6.

For further analysis of the longer period of 47 years (1950-1996), only 3-monthly averages were used. Figure 3 shows a plot of these 3-monthly values for the period 1950-1976 (first 27 years). Plot 1 is for El Niño (EN) 1+2 and shows the major events of 1951, 1953, 1957, 1965, 1969, 1972, and 1976 (shown in solid). Plot 2 (dashed curve) shows the Puerto Chicama SST values almost exactly similar to those of EN 1+2. Plots 3 and 4 for EN 3 and EN 4 are also very similar to those of EN 1+2, but the SST anomaly magnitudes are smaller. T-D is plotted upside down (as D-T) so that maxima match with SST maxima, which seems to occur except that some D-T maxima show structures. The North Atlantic SST maxima do not coincide always with the EN maxima. A glaring discrepancy was in 1972 when there was a very strong EN maximum but no North Atlantic SST maximum. Reverse discrepancies were in 1955, 1962, and 1966 when North Atlantic SST had maxima but there were no EN maxima. Similar discrepancies are seen for tropical ocean SST also, which showed no maxima during the 1951, 1953, 1957, 1965, and 1976 EN maxima, and the Indian Ocean SST, which showed no maxima during 1976 EN maximum.

Figure 4 shows plots for 1975-1998, with the very strong events of 1982-1983 and 1997-1998 reflected prominently in EN 1+2, SST Puerto Chicama (dashed curve), EN 3 and EN 4 (much reduced magnitude), and D-T. The smaller events of 1987 and 1992 are also reflected similarly. Figure 4 includes several other parameters. Thus, the 850-hPa trade wind indices in the west, central, and east Pacific low latitudes show marked decreases during the EN maxima. The equatorial outgoing long wave radiation (OLWR) shows decreases, but the Eurasian snow cover area does not seem to be related to EN maxima. The relationship with North Atlantic SST is dubious. Details for individual events are discussed in section 6. The Indian Ocean SST was obtained from the Reynolds (NCEP) reconstructed SST data and the Reynolds (NCEP) SST data.

For the whole period 1950-1997, correlations between the various parameters showed that all the EN were well intercorrelated and well correlated with SST of whole tropics and with T-D (correlations exceeding 0.5). Tropical SST, Indian Ocean SST, and T-D were also intercorrelated, but Atlantic parameters were poorly correlated with the other parameters. A cross-correlation analysis [Kane, 1999] showed maximum correlations of -0.65 between Pacific SST and North Atlantic SST and -0.45 between Pacific SST and South Atlantic SST, implying a common variance (square of correlation) of less than 40%, leaving 60% as independent variations. This partial independence of Pacific and Atlantic SSTs has important implications for the rainfalls in some regions, notably northeast Brazil.

4. Spectral Analysis

Correlations can be low either because the parameters are independent (zero correlation) or because the parameters have only a partial connection. To check whether there were any common periodicities between these parameters, their time series were subjected to a power spectrum analysis using the maximum entropy method (MEM) [Burg, 1967; Ulyych and

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**Figure 2.** Cross-correlations with respect to El Niño 1+2 as the primary parameter. Lag means the other parameter was lagging behind (attained maxima later in time). Note that all correlations are positive (zero line upward) except for plot 5 (T-D), where correlations are negative (zero line upward).
Figure 3. Plots of the 3-monthly means of the deseasoned values (four values per year) for 1950-1976.

Bishop, 1975], which detects periodicities much more accurately than the conventional Blackman and Tukey [1958] method does (hereinafter referred to as BT). Similar to the parameter lag $m$ in BT, MEM has a parameter called the length of the prediction error filter (LPEF), which can be chosen. With low LPEFs, only low periodicities are resolved. Larger LPEFs resolve larger periodicities, even those approaching the data length, but the errors are larger, and low periodicities show peak splitting. An LPEF equaling 50% of the data length generally gives good results.

MEM has a drawback, namely, the power estimates are not reliable [Kane and Trivedi, 1982]. Hence MEM was used only to identify the possible periodicities $T_k$, which were then used in the expression

$$f(t) = A_o + \sum_{k=1}^{\infty} \left[ a_k \sin(2\pi T_k t) + b_k \cos(2\pi T_k t) \right] + E$$

$$= A_o + \sum_{k=1}^{\infty} \left[ r_k \sin(2\pi t + \phi_k) \right] + E \quad (1)$$

where $f(t)$ is the observed series and $E$ is the error factor. A multiple regression analysis (MRA) [Bevington, 1969] was then carried out to obtain the best estimates of $A_o$, $(a_k, b_k)$, and their standard errors, by a least squares fit. From these, $r_k$ and their standard error $\sigma$ (common for all $r_k$ in this methodology) can be calculated, and any $r_k$ exceeding $2\sigma$ would be significant at a 95% (a priori) confidence level. Note that MEM and MRA are two independent procedures, in no way related to each other.

Some aspects of this methodology need to be emphasized here. Firstly, MEM peak detection is very, very accurate. For example, suppose the data are seasonal values (four values per year) for $-13$ years, that is, 52 data points. In conventional BT method, with a generally recommended lag $m$ of 25% of data length ($m = 13$ in this case), only certain frequencies $k/2m\pi$ can be investigated, that is, $1/26$, $2/26$, ..., $11/26$, $12/26$, $13/26$ (the folding frequency $0.5$). In terms of periodicities, these are 26, 13, ..., 2.36, 2.16, 2.00 years. Thus, if the periodicity was 2.25 years, it would be missed. In MEM there is no such restriction. Any frequency (of course, less than the folding frequency 0.5) can be investigated and the steps are a matter of choice. Thus, if about 70 steps are investigated between 2.0 and 3.0 years, the
periodicities could have a step resolution of 0.01 and a detection accuracy of 0.05 years or better. This was checked by feeding artificial samples [Kane, 1977, 1979]. MEM resolves peaks even slightly better than the criterion mentioned by Ulrych and Bishop [1975], namely, two frequencies $f_1$ and $f_2$ can be resolved if the data length exceeds $1/(f_1 - f_2)$. Since the amplitudes are finally estimated by MRA (MEM is used only for locating periodicities $T$), the main restriction comes from MRA. Here the standard error of all periodicities is equal (white noise). However, if two periodicities are too close, the method gives larger standard errors for both those periodicities. In general, a separation of 0.10 (e.g., 2.50 and 2.60) is enough for resolution.

There is also another apprehension usually expressed about MEM, namely, appearance of spurious peaks. In our investigation with artificial samples [Kane, 1977, 1979; Kane and Trivedi, 1982], no spurious peaks were ever observed except as splitting of low-periodicity peaks at very large LPEF (approaching the data length). An LPEF equaling 50% of the data length is generally a good, safe compromise and was used in the present analysis. However, to be more certain, all analyses were carried out for LPEFs equaling 33% and 66% of data length also, and only peaks common to all the three LPEF plots were chosen for further MRA.

Figure 5 shows the amplitudes of the various periodicities detected by MEM of each series. To check the transience of the periodicities, the data were divided into two equal portions, 1950-1973 (Figure 5a) and 1973-1996 (Figure 5b). The hatched portions indicate the 2σ limits, and peaks above this limit are significant at a 95% or better (a priori) confidence level. The following may be noted:

1. The El Niño regions have prominent SST peaks in the quasi-biennial oscillation (QBO) (2-3 years), quasi-triennial oscillations (QTO) (3-4 years), and higher periodicities. However, these are slightly different in the first 24 and last 24 years, indicating a probable transient nature of these periodicities.

2. A well-known atmospheric phenomenon having QBO is the low-latitude stratospheric zonal wind [Reed et al., 1961; Veryard and Ebdon, 1961]. The bottom plot of Figure 5a shows the spectra of 50-hPa zonal wind. The wind peaks at 2.01, 2.38, and 2.96 years are very similar to the peaks at 1.98, 2.42, and 2.96 years of EN 1+2, except that the 2.38-year peak is stronger than the 2.96-year peak in the wind but weaker in EN 1+2. However, the wind peaks have changed in Figure 5b. There is only one strong peak at 2.49 years, consistent with the comment of Naujokat [1986] that the wind QBO had a period of 26
Figure 5. Spectra (amplitudes of the various periodicities obtained by maximum entropy method, MEM) of the series of the various parameters for (a) 1950-1973, (b) 1973-1996, and (c) 1973-1996. The hatched portions represent the 2σ limits. Note that the abscissa scale is logarithm of periodicity $T$ (years).
months in the early days, which increased later to 27 months and still later to 28 months (nowadays, it is ~30 months). A possible coupling between stratospheric and tropospheric variations is indicated by Geller [1993] and Reid and Gage [1993].

3. The Atlantic parameters have very different periodicities. In Figure 5a the North Atlantic SST has peaks at 2.01, 2.25, 2.70, 3.79, and 5.4 years. The South Atlantic SST has peaks at 1.96, 2.33, and 3.42 years. MEM is very accurate in this region and periodicities can be detected and distinguished with an accuracy of 0.05 years or better. Hence only 2.01 of North Atlantic SST and 1.96 of South Atlantic SST could be the same as 2.01 of stratospheric wind. All other peaks are different for the North and South Atlantic and different from the wind peaks or the EN peaks. In Figure 5b these peaks are slightly different, again indicating a transient nature.

4. The \((N+S)/2\) Atlantic SST peaks are partly similar to the North Atlantic peaks. The SST \(N-S\) dipole has peaks at 1.99 and 3.93 years, matching with 1.98 and 4.00 years of EN 1+2. Again, these peaks changed in Figure 5b.

5. The Indian Ocean SST has very different peaks, 2.04, 3.38, and 4.75 years, again different in Figures 5a and 5b.

6. There are peaks in the 7- to 9-year and 11- to 14-year ranges in the EN parameters as well as in the Atlantic parameters. These too are different in Figures 5a and 5b.

Thus only a biennial peak (~2 years) seems to be common to all regions (including stratosphere) and may have an explanation in the Meehl [1987] mechanism. However, this is not the most prominent peak in any series. Another peak near 1.5 years, barely significant, seems to appear in many series. Also, the dominant scale is not the 4-6 years as mentioned by Nicholson and Nyenzi [1990], and there is considerable power in the QBO region. Selvam and Joshi [1995] analyzed 28 years (1961-1988) of September-November global air and surface temperatures and obtained periodicities which matched with the time periods of the internal circulation of the quasiperiodic Penrose tiling patterns, namely, 2.2, 3.0, 3.6, 5.8, 9.5, 15.3, and 24.8 years. These periodicities are not seen exactly in our results of any parameter.

Wright [1977] presented spectra for the Southern Oscillation Index for four intervals 1851-1882, 1881-1912, 1911-1942, and 1941-1972, and found 3- to 4-year and 5- to 6-year periodicities but with different strengths in different intervals. On the other hand, Landsberg et al. [1963] and later Rasmussen et al. [1990] emphasized the biennial component (2-year periodicity) of ENSO variability. Recently, Zhang et al. [1998] used multichannel singular spectrum analysis to characterize the spatiotemporal structure of the interannual and interdecadal variability of Pacific SST and identified a quasi-quadrennial oscillation (QQO) of period 51 months (4.3 years) and a QBO of 26 months (2.17 years). These are obviously average values and cannot be compared with the fine structures and variations with time that we observed in the equatorial region. However, Zhang et al. conducted their analysis for a much wider latitude belt (20°S- 58°N) and were able to note that the QQO of SST propagated northeastward from the Philippine Sea and then eastward along 40°N but behaved more like a standing wave.
over the tropical Pacific, while the QBO of SST was localized in
the tropics and propagated westward near the equator.

Figure 5c shows spectra for other parameters. The 850-hPa
trade winds in the eastern Pacific (120°-130°W) have a
prominent peak at 4.31 years and secondary peaks at 3.44 and
2.04 years. For the central Pacific (140°-175°W) these peaks
shift to 4.64, 3.69, and 2.34 years. For the western Pacific (180°-
130°E) there is a further shift to 5.2, 3.90, and 2.46 years. These
shifts are significant and may have important implications for
the dynamics of the phenomenon. This needs further
investigation. The peaks do not match completely with the SST
peaks for EN 1+2, EN 3, and EN 4 regions. The Eurasian snow
cover area has peaks at 2.16, 4.51, and 7.9 years. As an
additional parameter, the series for the snow cover area for the
whole Northern Hemisphere (NH) was analyzed and gave peaks
at 2.15, 3.52, 4.28, and 7.8 years.

For a study of longer periodicities, annual values were used.
Figure 6 shows the plots (one value per year) for 1950-1996. As
can be seen, there are wide fluctuations with peak spacings of 2-
5 years, indicating the presence of periodicities in this range. To
minimize their effect, 5-year running averages were calculated
and are shown as the superposed thick curves in Figure 6, while
amplitudes of periodicities obtained by a spectral analysis of
these 5-year running averages are shown in Figure 7. As can be
seen, most of these parameters now show prominent
periodicities in the QTO and higher periodicity regions, but
different longitudes show different periodicities. There is little in
common between the Pacific and the Atlantic and other regions.
Many earlier workers have reported coherence between different
regions in broad spectral bands, namely, QBO, QTO and higher
periodicities. However, the finer analysis presented here
indicates that in these bands, the periodicities are not alike.

In the higher-periodicity region, several studies have been
reported by other workers. For surface air temperatures, Deser
and Blackmon [1993] made an EOF analysis which revealed a
significant peak near 11 years for air temperature over the North
Atlantic; the corresponding EOF was a dipole near the east coast
temperature analysis, which revealed significant 11- to 12-year
peaks. Regional analysis showed stronger 11-year signals in the
Northern Hemisphere over northern Europe and Greenland and
in the Southern Hemisphere at high latitudes but weaker
variability at low latitudes. Kane and Teixeira [1990] reported
significant peaks near 11 years in the surface temperature of the
Northern Hemisphere but not of the Southern Hemisphere. Thus
a sunspot cycle effect was indicated. However, Mehta and
Delworth [1995] obtained quasi-decadal oscillations in
numerical ocean-atmosphere models for the Atlantic Ocean,
without any external forcing. Mehta and Lau [1997] used long
series (more than 100 years) of EN 3 region SST and rainfall
over India and showed that their covariability had decadal-
multidecadal variations without any distinct periodicities.

Atlantic SST. The difference could be because of the shorter
length (47 years only) of our data. Mehta identified three modes
of decadal variations in the Atlantic SST, two in the North
Atlantic (a more energetic and a less energetic) and one in the
South Atlantic, and described their motions with time along the
eastern and western boundaries of the Atlantic basin. However,
these decadal modes were not a permanent feature of the tropical
Atlantic SST variations. The north northeast Brazil rainfall
showed physical consistency with the cross-equatorial Atlantic
SST gradient oscillation at 12- to 13-year period. A similar
result is reported by Kane [1997d], where prediction
possibilities using these periodicities are discussed.

5. Trends

From the plots in Figure 6 for the 5-year running averages, it
seems that some parameters have long-term trends. However,
these do not seem to be uniform. Figure 8 shows a plot of 11-
year running averages, and it is seen that the trends are different
in the first 23 years as compared with the last 23 years. The
transition (determined by a rough visual inspection) is marked
by the vertical lines on each plot. A statistical trend analysis was
conducted for 1952-1973 and 1974-1994 separately, using the
5-year running averages. The decadal trends (change over 10
years) so obtained are given in Table 2. In the first 22 years
(1952-1973) some correlations are low and the trends are
insignificant, but other correlations are reasonably high, and the
trends are significant. Among these, the significant trends are
+0.21°C (per 10 years) for South Atlantic SST, -0.29°C for the
Atlantic SST dipole (N-S), and +0.16°C for the Indian Ocean SST. In the latter 21 years (1974-1994), correlations are better, and the large trends are +0.37°C for EN 4 region SST, +0.69 hPa for Darwin minus Tahiti pressure difference, +0.15°C for South Atlantic SST, +0.21°C for whole tropics SST, and +0.24°C for the Indian Ocean SST. Comparing the first and the last 21 years, EN 4 SST, whole tropics SST and D-T pressure difference developed large trends only in the latter half, while the South Atlantic and Indian Oceans’ SSTs had consistently upward trends in both halves. The North Atlantic trend was small negative in the first half and small positive in the second half. As a result, the average Atlantic (N+S)/2 had an upward trend in both halves, and the Atlantic dipole (N-S) had a downward trend in both halves. In short, SSTs at different longitudes had different long-term trends. Therefore the origins of these spectra and trends in different longitudes should be different. A similar nonuniformity of long-term trends in ground temperatures and some tropospheric, stratospheric, and mesospheric parameters was reported by Kane [1996, 1997c]. Incidentally, the bottom plots in Figure 8 show that the snow

<table>
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<tbody>
<tr>
<td>EN 1+2</td>
<td>+0.04</td>
<td>+0.09±0.07</td>
</tr>
<tr>
<td>EN 3</td>
<td>+0.07</td>
<td>+0.02±0.05</td>
</tr>
<tr>
<td>EN 4</td>
<td>+0.25</td>
<td>+0.09±0.07</td>
</tr>
<tr>
<td>Darwin-Tahiti</td>
<td>-0.20</td>
<td>-0.11±0.12</td>
</tr>
<tr>
<td>North Atlantic</td>
<td>-0.48</td>
<td>-0.08±0.03†</td>
</tr>
<tr>
<td>South Atlantic</td>
<td>+0.82</td>
<td>+0.21±0.03*</td>
</tr>
<tr>
<td>(N+S)/2 Atlantic</td>
<td>+0.61</td>
<td>+0.07±0.02*</td>
</tr>
<tr>
<td>Tropical</td>
<td>+0.52</td>
<td>+0.07±0.03†</td>
</tr>
<tr>
<td>N-S dipole Atlantic</td>
<td>-0.78</td>
<td>-0.29±0.05*</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>+0.77</td>
<td>+0.16±0.03*</td>
</tr>
</tbody>
</table>

All trends are given in degrees Celsius per 10 years, except Darwin-Tahiti which is given in decibars. Corr.coeff., correlation coefficient.
* Significance is better than 3σ.
† Significance is 2σ.
cover areas in Eurasia as well as the whole Northern Hemisphere had a downtrend since about 1980 till 1992. Thus the temperature uptrends seem to have caused snow melting in recent years.

Zhang et al. [1998] have mentioned an interdecadal mode, which is a standing mode with opposite signs of SST anomalies in the North Pacific and in the tropical Pacific, with an amplitude in the central North Pacific that is larger than that in the tropical Pacific. Since around 1976-1977, this mode is associated with cooling in the central North Pacific and warming in the equatorial Pacific. The recent uptrends could be a manifestation of this interdecadal mode. Conversely, the recent uptrend may be an irregular feature of anthropogenic origin and may show mathematically as an apparent interdecadal mode of long periodicity.

6. Individual Major Events

A casual examination of Figures 1-8 indicates that the SST anomalies at different longitudes probably have independent characteristics and that their relative juxtapositions may not have a clear lag-lead pattern. The positioning was examined for some El Niño years, namely, 1951, 1953, 1957, 1963, 1965, 1969, 1972, 1976, 1983, 1987, 1992, and 1997. For each, the lags or leads of all parameters were counted with the El Niño 1+2 region as the reference (zero epoch). Figure 9 shows the results. In the top plots, the seasons when El Niño 1+2 SST had maxima are considered as the zero epochs. In the first column the twelve columns for the 12 events (months and years marked at the right) for El Niño 3 are all within 1 or 2 seasons of the zero epoch (vertical dashed line), indicating that El Niño 3 evolution is closely associated with El Niño 1+2 evolution. The same is true for El Niño 4 shown in the second column, though here the evolution could be delayed by as much as 3 seasons. In the third column for Darwin minus Tahiti pressure difference D-T, the lags or leads are generally within one season. However, in the fourth and fifth columns for North and South Atlantic SST, the lags or leads for SST maxima or minima seem to vary considerably, up to 4-5 seasons. The sequence of the 12 events is so arranged that events starting earlier in the calendar year are considered first. Most of the earlier events had EN 1+2 SST maxima (3-monthly means) centered in May, and the rest were centered in August. The scatter does not seem to depend on this factor. In some events, Atlantic SST maxima or minima did not exist. The scatter and absence of maxima or minima are also seen in the parameters (N+S)/2 and (N-S) in the Atlantic (sixth and seventh columns) and in Indian Ocean SST (eighth column). Thus outside the Pacific region, the SST variations do not accompany the Pacific variations with any certain lag or lead pattern. As such, the Pacific or Atlantic or Indian Ocean's SST maxima or minima are not likely to be useful as predictors of each other. From the 12 El Niño events considered here, 9 had north Atlantic SST maxima with lags within ±4 seasons, while 3 had no association with North Atlantic SST maxima but had
association with North Atlantic SST minima. In the case of other parameters too, similar situations occurred.

In the bottom plots of Figure 9 the zero epoch corresponds to El Niño 1+2 SST anomaly commencements (instead of SST maxima), and the lags and leads refer to the commencements of SST anomalies in the other parameters. The results are similar to those in the top plots.

Using the Comprehensive Ocean-Atmosphere Data Set (COADS), Nicholson [1997] conducted harmonic analyses of the ENSO composites (methodology same as that of Ropelewski and Halpert [1987, 1989]) of 4° x 4° grid SST data in the tropical Atlantic and western Indian Oceans, for the eight El Niño episodes of 1951, 1953, 1957, 1963, 1965, 1968, 1972, and 1976. (All these episodes are included in our Figure 9 except 1968, which is 1969 in our case). Considering these years as zero (year 0) epochs, a first half of every Pacific episode was considered as July of year -1 to June of year 0, and the second half was considered as July of year 0 to June of year +1. Nicholson reported that in the composites for three successive months, in the July-August-September (JAS) (year -1) and October-November-December (OND) (year -1) seasons, cold anomalies (SST below normal) prevailed in the whole area, minima occurring in the OND (year -1) season for the Atlantic and in the January-February-March (JFM) (year 0) season in the Indian Ocean. In the southeast Atlantic, warming began in JFM (year 0) and intensified in April-May-June (AMJ) (year 0). Elsewhere in the Atlantic and Indian Oceans, warming commenced later, in JAS (year 0), and persisted until the following year. The Atlantic as a whole reached peak warming around OND (year 0), and the Indian Ocean reached peak warming one season later, during JFM (year +1). Thus, according to Nicholson [1997], the tropical Atlantic lagged the eastern Pacific (El Niño 1+2) by ~6 months but was roughly in phase with the central Pacific (El Niño 3). The Indian Ocean lagged both by an additional 3 months. Since our analysis deals with low latitudes only, only a low-latitude strip at different longitudes is considered by us. Also, in our Figure 9, the zero epochs are El Niño 1+2 maxima in the top plots and commencements in the bottom plots, and calendar seasons as such are not involved. However, it happens that among the 12 events, 6 had EN maxima in May, and the other 6 had maxima in August. Thus some calendar season identification is possible. For the first six events the zero is May, and according to the pattern described above, the part far to the left of the zero line should have had crosses (SST minima), and the part to the right should have had circles (SST maxima). Roughly the same should have happened for the other six events. For all these events, +2 and +3 seasons are roughly the OND (year 0) and JFM (year +1) months and should have shown a preponderance of circles (warming) in the Atlantic and Indian Oceans. Instead, erratic distributions are seen in Figure 9, in the fourth-eighth columns. Thus the patterns mentioned by Nicholson are not seen. Further, as a result of harmonic analysis of the composites (24 monthly values), Nicholson identified 10 Atlantic Ocean sectors and 7 Indian Ocean sectors which showed coherent ENSO response, namely, a cool phase in both oceans (Atlantic and Indian) in the first half of the ENSO cycle and a warm phase in the second half. However, though many of these sectors were in low latitudes, the amplitudes of the harmonic waves rarely reached 0.5°C. Our SST plots of North and South Atlantic anomalies (Figures 3 and 4) often show magnitudes approaching 1°C and lasting for several seasons continuously, sometimes before the EN maxima. It seems, therefore, that the regular patterns mentioned by Nicholson reflect only a small part of the actual variations, and the rest of the variations have some other, local origins. Nicholson [1997, p. 356] is aware of such discrepancies but feels "that the inconsistency in the ENSO signal is more in its timing than in its presence or absence in the Atlantic and western Indian Oceans". Nicholson, while noting that some ENSO episodes were manifested less strongly than others in the tropical Atlantic and Indian Oceans, did not find any distinguishing characteristics. Also, the patterns during the 1982-1983 and 1986-1989 events were somewhat different from the average patterns for the earlier eight events. In our view, this indicates considerable contributions from other, local sources, and the ENSO relationship in the Atlantic and Indian Oceans is certainly not as secure and clear-cut as is indicated above.

Recently, a strong El Niño occurred in 1997-1998. In Figure 9, this event is also considered (top plots, lowermost event). EN 1+2 attained a broad maximum during July-December 1997 (see Figure 4) and is considered here as in August 1997. North Atlantic SST attained a maximum roughly 1 season later and the South Atlantic minimum occurred roughly 1 season earlier. In the bottom plots of Figure 9 the sixth event has March 1997 as
the commencement of the EN 1+2, and the North Atlantic positive SST, South Atlantic negative SST, and Indian Ocean positive SST all seem to commence near March 1997. Figure 10 shows a detailed plot of the monthly values of this 1997-1998 El Niño event. The following may be noted:

1. In the EN 1+2 region (plot 1) the event started in February 1997, reached a peak in July, remained at that level till December 1997, and then declined. In the EN 3 region (plot 2), the commencement was in March 1997, and there was a sharper peak in November 1997 and a decline thereafter. In EN 4 region (plot 3) the commencement was in January 1997, and a broad peak started in April 1997 and lasted up to December 1997, declining thereafter. Allowing for threshold uncertainties, the event may be considered as starting in February-March, 1997. The SST positive anomalies (increases) are shown solid and the negative anomalies (decreases) are shown hatched.

2. Darwin minus Tahiti pressure difference D-T increased (solid portion) abruptly in March 1997, and the peak was in the early months of 1998, with a sharp decline thereafter (plot 4).

3. The 850-hPa trade wind index, expected to decrease during El Niños, is plotted upside down, and the decreases are solid. The decrease started in March 1997, more abruptly in the west Pacific (135°E-180°E, plot 7). It lasted longer in the 120°W-130°W longitude belt (plot 5), peaking in the early months of 1998, like D-T. In the 140°W-175°W belt also (plot 6), the event started in March 1997, and the peak was in the early months of 1998, but the decline thereafter was sharper. In the 130°E-180°E belt (plot 7) the event started in March 1997 and was of a short duration, declining sharply after October 1997.

4. Whole tropics SST event (plot 8) started in March 1997 and evolved like EN 1+2.

5. The outgoing long wave radiation (OLWR) (W/m²) seemed to be negatively correlated to the SST (see Figure 4) and is plotted upside down (plot 9), with the decreases shown as the solid portion. The start was in March 1997, and end was in October 1997.

6. Thus all these parameters started almost simultaneously (February-March, 1997) with the Pacific EN 1+2 event, but the durations were different.

7. For this event the Nicholson [1997] method would designate 1997 as year 0, 1996 as year -1 and 1998 as year +1. (1) According to Nicholson, cold anomalies (negative SST anomalies) should have prevailed in the whole region (Atlantic and Indian Oceans) during JAS (year -1) and OND (year +1), during the last 6 months of 1996. Instead, the Atlantic SST anomaly was large positive, in both the North and South Atlantic (plots 10 and 11), for several months in 1996 and was not negative even in the end of 1996. (2) Maximum cooling should have occurred during OND (year -1) season for the Atlantic as a whole. No such cooling was observed in OND of 1996. (3) In JFM of 1997, warming should have started in the southeast Atlantic, intensifying in AMJ of 1997. Instead, such warming occurred in the North Atlantic only, while the South Atlantic showed cooling, in the first few months of 1997. (4) The Atlantic as a whole should have reached peak warming in OND 1997. This seems to have come true. North Atlantic, South Atlantic and their average (N+S)/2 (plot 12) showed large positive anomalies in OND 1997. According to Rasmusson and Carpenter [1982], the tropical Atlantic should lag the eastern Pacific by ~6 months but should be roughly in phase with the central Pacific. Hamilton and Allingham [1988] concluded that the maximum warming in the Atlantic as a whole occurs during the “mature” phase of ENSO toward the end of year 0. This came true.

8. The dipole (N-S) (plot 13) showed large negative anomalies in 1996, large positive anomalies in early 1997, and large negative values in late 1997.

9. In the Indian Ocean (plot 14) the SST changes up to the middle of 1997 were small, smaller than those in 1982-1983, 1987, 1991, and 1994 (see Figure 4). There was a small decrease in OND of 1996 and a small increase since March 1997, coinciding with the EN changes. Thus the Indian Ocean SST did not lag behind the Pacific.

10. The Eurasian snow cover area (plot 15) shows a slight decrease during mid-1997. However, similar decreases occurred earlier in 1988 and 1990 (see Figure 4).

In short, whereas some parts of the SST evolution in the Atlantic during this strong El Niño of 1997, particularly the peak phase, are in agreement with the average pattern, some other parts, notably in the pre-event phase, have been very different from the average pattern reported by Nicholson [1997]. For obtaining the average pattern, Nicholson used the eight events of 1951, 1953, 1957, 1963, 1965, 1968, 1972, and 1976; however, the strong event of 1982-1983 was not included, and a separate study of the same showed some unusual characteristics. Thus the two strongest events of this century so far, 1982-1983 and 1997-1998, did not conform to the average pattern completely, in disagreement with the claim of Servain [1991] that the average patterns are most pronounced for extreme ENSO events. The Nicholson (Servain) patterns can be broadly divided into two phases: (1) the mature phase, where SST anomalies in all regions are positive, and (2) the pre-event phase when Atlantic SSTs show negative anomalies. In general, phase 1 was seen more or less satisfactorily; but phase 2 was not seen convincingly. This is unfortunate, because the pre-event negative anomalies of Atlantic SST could be precursors of the El Niño event.
accounted for some discrepancies but not all. Obviously, other classification of El Niño events [Kane, 1997a, b, 1998a, b] often partial. Some El Niño years do not show expected rainfall extremes [Ropelewski and Carpenter, 1983]. A finer classification of El Niño events [Kane, 1997a, b, 1998a, b] accounted for some discrepancies but not all. Obviously, other factors must be interfering. In the case of India, relationships with Himalayan and Eurasian snow covers, SST and wind speed over the central Arabian Sea, stratospheric wind QBO, and the latitudinal location of the axis of the 500-hPa ridge along 75°E are reported [Kane, 1997a, b, 1998a, b, and references therein]. Presently, attempts are made to apply statistical models using three types of predictors, namely, upper air flow over India, heat low development over southern Asia and meridional pressure gradient and cross-equatorial flow over the Indian Ocean, and the Southern Oscillation [Thapliyal and Kulshrestha, 1992]. Long-range seasonal forecasts for the southwest monsoon rainfall for Indian summer (June-September) are issued by the India Meteorological Department (IMD) sometime in every May. For the last few years this scheme is giving very good predictions for the June-September Indian summer monsoon rainfall.

In Australia, several empirical and model studies link SST anomalies in the waters around Australia with rainfall regimes. Wetter years for the whole of Australia are linked to warmer SSTs in middle and low latitudes, while rainfall in eastern Australia is related to variations of SSTs in the north Australian-Indonesian region [Streten, 1981, 1983; Meehl, 1987; Simmons, 1990; Allan et al., 1990; Lough, 1992, and references therein]. Many of these SST relationships, for example, for eastern Australia, are related to ENSO influences [Ropelewski and Halpert, 1987, 1989]. For rainfall in Queensland, Lough [1992] examined the seasonal SST anomalies off NE Australia (0°-30°S, 130°-180°E) and concluded that the western Pacific cannot be considered as a single region. Part of the area (northeastern part) varied in association with the central equatorial Pacific (El Niño 4 region), and even in the rest of the region, there were spatial differences. In Queensland, SST variations were linked more closely with winter rainfall than with summer rainfall, but both were closely related to ENSO [see also Streten, 1983; Whetton, 1990; Smith, 1994]. For nearby New Zealand, Mullan [1998] found that the SST in the immediate vicinity was correlated to the SST in the Tasman sea and south Australia and that warmer Indian Ocean waters in autumn were followed by wetter conditions in west South Island and drier conditions in other parts of New Zealand.

In Africa, rainfall regimes in different parts are very different, and most of these seem to have poor ENSO relationships, except eastern and southern Africa [Dyer, 1979; Lindesay et al., 1986; Janowiak, 1988; Nicholson and Entekhabi, 1986]. On the other hand, considerable influences of SST anomalies are reported. For subsaharan rainfall many workers have discussed the role of tropical Atlantic SST [Lamb, 1978a, b; Lough, 1986; Drayan and Hastenrath, 1991; Janikot, 1992; Folland et al., 1991; Fontaine and Bigot, 1993]. For equatorial and southern Africa, Nicholson and Entekhabi [1987] studied the relationship with SST along the southwestern coast of Africa. For South Africa, Tyson [1981] showed the association with pressure changes in the surrounding environment, and Mason [1990, 1995] invoked the temporal variability of SST around South Africa. Recently, Nicholson and Kim [1997] made a comprehensive study of the rainfall response over Africa to ENSO episodes. The strongest signals were reported to have appeared in southern, eastern, and far northern Africa, and weakest signals were reported in the Sahel. There was a general tendency for positive rainfall anomalies in the first half of the ENSO cycle and negative rainfall anomalies in the second half. Comparing the rainfall results with those of SST by Nicholson [1997], Nicholson and Kim conclude that the ENSO episodes that influence rainfall over Africa are those which are manifested as SST fluctuations in the low-latitude Atlantic and western Indian Oceans.

7. Rainfall Relationships

El Niño occurrences are popularly believed to be associated with extremes of rainfall in many parts of the globe. Ropelewski and Halpert [1987] reported that besides regions in the Pacific Ocean basin, four regions in Australia; two regions each in North America, South America, the Indian subcontinent, and Africa; and one region in Central America were found to have coherent ENSO-related response. However, these responses are often partial. Some El Niño years do not show expected rainfall extremes [Rasmussen and Carpenter, 1983]. A finer classification of El Niño events [Kane, 1997a, b, 1998a, b] accounted for some discrepancies but not all. Obviously, other factors must be interfering. The El Niño started much earlier (February-March 1997) and was already exceptionally strong by mid-1997. Thus the models are by no means perfect. Often, the predictions from different models differ considerably.

Figure 11. Evolution of the 1997-1998 El Niño in the equatorial belt (6°N-6°S) at successive 30° longitude belts, centered 30° apart (Reynolds SST data), excluding the Atlantic basin and the Caribbean sector. Arrows indicate the commencements of the positive SST anomalies (solid). Negative anomalies are shown hatched.
For northeast Brazil a considerable influence of tropical Atlantic SST was reported long ago [Markham and McLain, 1977]. Other factors considered are 700-mbar circulation pattern over the North Atlantic [Namias, 1977], meridional displacement and strength of the Intertropical Convergence Zone (ITCZ) [Hastenrath and Heller, 1977], rainfall systems associated with tropical disturbances moving westward from the Atlantic toward northeast Brazil [Ramos, 1975; Yamazaki and Rao, 1977; Rao et al., 1993], and Southern Hemisphere cold fronts or their remains moving northward along the northeast coast of Brazil [Kousky and Chu, 1978; Kousky, 1979]. Hastenrath et al. [1984] and Hastenrath [1990] formulated prediction schemes involving zonal and meridional wind components over limited areas of the equatorial Atlantic, SST in the tropical North and South Atlantic, Southern Oscillation (SO) Index, and preseason rainfall itself in northeast Brazil as predictors. In a recent communication, Hastenrath and Greischar [1993] and Hastenrath and Druyan [1993] reported further modifications. Earlier, Servain and Seva [1987] had investigated the relationship between tropical Atlantic SST, wind stress, and regional precipitation indices and shown that for the seasonal timescale the northward displacement of the ITCZ was accompanied by the strengthening of the southeast trades and/or relaxation of the northeast trades, which is correlated with a decrease in northeast Brazil rainfall. Wainer and Soares [1997] showed that for northeast Brazil this was true on an interdecadal timescale also.

Ward and Folland [1991] investigated the relationship between north northeast Brazil rainfall and SST in various parts. For the Atlantic they reported correlations similar to those reported earlier by Markham and McLain [1977], namely, positive correlation with SST in the south tropical Atlantic and negative correlation with SST in the north tropical Atlantic. For the tropical Pacific, negative correlations extended over a wide area, implying a relationship with the El Niño-Southern Oscillation phenomenon, earlier reported by Covey and Hastenrath [1978]. Further, Ward and Folland calculated the covariance eigenvectors for SST in the Atlantic and Pacific Oceans and studied the relationship of the various eigenvectors with north northeast Brazil rainfall. Forecasts were made for 1987, 1988, 1989, and 1990 and were found to be good. Since 1990, forecasts are available in February. The two predictors used are (1) the 30°N-30°S third EOF eigenvector of Atlantic SST for all seasons (reflecting the SST anomaly immediately off the north northeast coast of Brazil and the large-scale north-south SST gradient structure in the Atlantic) and, (2) the first EOF of Pacific SST for December-January-February, serving mainly as ENSO index. The forecasts for the 10 years 1987-1996, given by Colman et al. [1997], matched very well in the earlier years but only approximately in recent years. The worst forecast was for 1996, probably because of a sharp change in Atlantic SST through the forecast season. Forecasts by this statistical approach as well as by other methods involving an atmospheric general circulation model (GCM) have been given by several other workers for northeast Brazil rainfall since 1993. These are discussed in great detail by Kane [1999]. Whereas forecasts for earlier years were reasonably correct, forecasts for 1996 were miserably poor in all these methods, probably because of the rapid changes in Atlantic SST during the forecast season, as mentioned by Colman et al. [1997].

Results for the 1997-1998 El Niño are also discussed in detail by Kane [1999]. In India there were no droughts in 1997 and 1998. Considering various other factors besides El Niño, IMD had predicted almost normal rainfall for both these years. The IMD prediction came true. The forecasts for northeast Brazil rainfall issued in January 1997 were mostly of moderately dry conditions [Colman et al., 1997; Harrison et al., 1997; Graham, 1997; Greischar and Hastenrath, 1997]. The observed rainfall in northeast Brazil in March-May 1997 was a few percent below normal in some parts and normal in others, thus, basically conforming to the above predictions. These predictions, made in January 1997 when the present El Niño had not yet commenced, were mainly influenced by Atlantic parameters, and yet, the predictions proved correct. As such, the development of El Niño later did not seem to have been of much consequence. The El Niño was still strong in the first few months of 1998 and weakened after May 1998. Thus it was still strong in the main rainy season (March-May, 1998) of northeast Brazil. In the end of 1997 a SST dipole was developing in the Atlantic, and the January 1998 forecast by Colman (private communication, 1998) of the Hadley Center, U.K. Meteorological Office, Bracknell, England, for northeast Brazil was of slightly wet conditions. An updated forecast given in the experimental long-lead forecast bulletin [Colman et al., 1998] prepared in early March 1998 using February 1998 SST also seemed to indicate wet conditions. However, it was also mentioned that given the continuing strong El Niño and the fact that the atmospheric model placed positive (wet) anomalies over the northeast, the possibility of a dry or very dry season should also be considered. In the same bulletin, Greischar and Hastenrath [1998] also predicted wetter than normal conditions but pointed out that whereas the preseason northeast rainfall and the meridional SST gradient in the Atlantic sector point to abundant March-June 1998 precipitation, the equatorial Pacific SST and the field of the meridional wind component in the Atlantic sector favor drier conditions. Hence the precipitation should be only slightly above average. In the same bulletin, Evans et al. [1998] predicted below average rainfall across the region except over northeast Brazil, while Cavalcanti et al. [1998] reported predictions based on a global spectral model [Kinter et al., 1988] and a sophisticated biosphere model [Xue et al., 1991]. Their prediction was of a below average precipitation over much of northeast Brazil. In reality, the main rainy season in northeast Brazil (March, April, and May) in 1998 suffered one of the severest droughts in known history. It will naturally be attributed to the 1997-1998 El Niño, again the strongest in known history. Thus, in spite of the progress in understanding the mechanisms that affect rainfall in northeast Brazil, predictions are still hazardous, could differ considerably from one model to another, and could be widely in error. It may be noted that whereas Cavalcanti et al. succeeded in predicting the 1998 droughts in northeast Brazil, the European Center for Medium Range Weather Forecasting (ECMWF) also predicted the 1998 droughts.

An important conclusion from these observations is that at least for northeast Brazil, both the Pacific SST and Atlantic SST are important, and for prediction purposes both these need to be taken into consideration, because these are only partially related and may sometimes neutralize the effects of each other. Had the Atlantic and Pacific SSTs been very well correlated (very good teleconnection), both these need not have been taken into consideration for predictions. Any one would have been enough. However, for the main rainy season March-May, predictions are based on the preceding December-January conditions of the Atlantic SST. If these conditions change rapidly in January or soon thereafter, the rainfall predictions for March-May may prove erroneous.

8. Conclusions and Discussion

The characteristics of SST were studied for low latitudes in the Pacific, Atlantic, and Indian Oceans for the period 1950-1996 (47 years). The following was noted:
1. All these regions had an average seasonal variation (in spite of the low latitudes), with maxima in March-April and minima in August-October and with ranges of 6°C in the El Niño I+2 region (80°W-90°W), 2°C in the El Niño 3 region (90°W-150°W), −0.5°C in the El Niño 4 region (150°W-160°E), −1.5°C in the Indian Ocean (60°E-90°E), and −1°C in the Atlantic region (40°W-10°E). The North Atlantic had a maximum in September-October and minimum in February-March, with a range of −2.5°C, while the South Atlantic had a roughly reverse pattern (maximum in March-April) but a much larger range (−4.0°C), yielding a range of −1°C for their average (north-south).

2. When the monthly values were deseasoned by subtracting the average seasonal patterns, considerable SST anomalies were observed in the deseasoned values. In the El Niño regions these were the well-known El Niño events with SST anomalies of 2°C or more, starting in the El Niño I+2 region first, lasting for several months, and spreading to the El Niño 3 and 4 regions within a few months. These were well-accompanied by the minima of the Southern Oscillation Index represented by the Tahiti minus Darwin atmospheric pressure difference (T-D).

3. In the Atlantic, similar changes (maxima in North Atlantic SST and minima in South Atlantic SST) were often seen, but their coincidence with the El Niño SST maxima was uncertain, often occurring with phase lags or leads of several months.

4. In the Indian Ocean also, the situation was similar.

5. The tropical SST (average for all longitudes) had variations similar to those of the El Niño regions, mainly because of the large magnitudes in the El Niño region and also because the variations at other longitudes were not coherent.

6. The spectral characteristics of the SST variations at different longitudes were different from each other and also different for the first 24 years (1950-1973) and the last 24 years (1973-1976). In the first 24 years, El Niño regions, T-D and whole tropics had strong peaks near 2.9, 4.0, and ~6 years, with a small peak at ~2 years. The Indian Ocean had peaks near 2.0, 3.4, and 4.8 years. The North Atlantic had peaks near 2.0, 2.25, 2.70, 3.8, and 5.4 years while the South Atlantic had peaks near 1.96, 2.33, and 3.42 years. The well-known phenomenon of stratospheric (50-hPa) low-latitude zonal winds had Quasi-biennial oscillations (QBOs) with peaks at 2.01, 2.38 (major peak), and 2.96 years, the last one matching with an El Niño peak. In the latter 24 years, El Niño regions, whole tropics and Indian Ocean had strong peaks near 2.5, 3.6, and 4.7 years, while T-D had peaks at 2.4, 3.4, and 4.6 years. The North Atlantic had peaks at 2.15, 2.46, 3.4, and 4.1 years, while the South Atlantic had just one strong peak at ~5 years. The 50-hPa wind had just one strong peak at 2.49 years. During this interval, Pacific trade winds had peaks near 2.04, 3.44, and 4.31 years in the 120°W-130°W region; 2.34, 3.69, and 4.64 years in the 140°W-175°W region; and 2.46, 3.90, and 5.2 years in the 180°E-130°E region. (Note the peak shifts). The outgoing long wave radiation at the equator in the 160°W-160°E region had peaks at 2.45, 3.58, and 4.86 years, while the Eurasian snow cover area had peaks at 2.16 and 4.51 years. Thus not all these peaks match with each other. (The analysis was done by using maximum entropy method, which gives periodicities with an accuracy of 0.05 years). For the whole interval 1950-1996, significant periodicities were observed at 8-10, 11-12, and ~19 years in many parameters. These could be solar cycle and lunisolar M<sub>n</sub> signals [Currie, 1996], though other origins are not ruled out.

7. Most of the parameters have long-term trends, different for the first half and the latter half. For the El Niño regions, D-T and whole tropics, the trend is negligible in the first half and rising in the second half. For the North Atlantic there is probably an overall decreasing trend, while for the South Atlantic and Indian Ocean there is an overall increasing trend. Thus some warming in some longitudes is indicated, particularly in the last 25 years. In this interval, Eurasian as well as Northern Hemisphere snow cover areas have decreased, indicating snow melting due to warming.

These results are not in complete agreement with those of Hastenrath and Kaczmarczyk [1981], who mention that the variance in the El Niño region is concentrated at ~2-8 and ~15 years, while in other regions it is in the long end of the spectrum. In the present case, all regions show QBOs, quasi-biennial oscillations (QBOs), and higher periodicities. Only, these do not tally exactly, and hence spatial linkages (teleconnections) on very large scales are doubtful. Hastenrath and Kaczmarczyk mention several characteristics of sea level pressure (SLP) that are not studied here. Sperber and Hameed [1993] suggested that the Walker circulation and the tropical Atlantic circulation interact on timescales of 12, 9, 6, 3.6, and 2.1 years. This is only broadly true. The periodicities in the Pacific and Atlantic are roughly in these bands, but individual values differ significantly, so that a common origin hypothesis is difficult to sustain. Hameed et al. [1993] suggested that Atlantic and Pacific conditions are related not via an oceanic signal from the Pacific but by changes in the atmospheric Walker circulation; the meridional circulation envisaged by Moura and Shukla [1981] and the SST gradients in the Atlantic are at least partly due to ENSO changes. Recently, Nobre and Shukla [1996] used EOF analysis to investigate the development of SST anomaly patterns over the tropical Atlantic and found that atmospheric circulation anomalies precede the development of basin-wide anomalous SST patterns. Further, they presented observational evidence to show that the ENSO phenomenon in the Pacific influences atmospheric circulation patterns and SST anomalies over the tropical Atlantic through atmospheric teleconnection patterns into higher latitudes of the Northern Hemisphere. However, all these results are based on EOF analyses and composites, and whereas the basic patterns may be valid and of great academic value, individual events show considerable deviations from the average patterns, even for strong events. Correlation analysis yields correlation coefficients between Atlantic and Pacific SSTs of less than 0.65, implying a common variance (square of the correlation) of the order of 0.40 or 40% only. Thus the teleconnection is only ~40%, while random variation (each region behaving in its own way) is ~60%, making the teleconnection between Pacific and Atlantic SSTs tenuous. The rainfall regimes are considerably influenced by SSTs in one region or other, so that the influence of El Niños may not be always obvious. This is seen glaringly in northeast Brazil where positive effects (excess rains) due to Atlantic SSTs can neutralize (or even reverse) the El Niño effects (droughts). Whereas a considerable part of the scientific community is aware of this situation, the media (press, radio and television) seems to be oblivious to the same. As soon as an El Niño appears on the scene, all weather and climate vagaries are attributed to it by the mass media, but the knowledgeable scientists do not seem to be particularly bothered about removing this misconception. The recent El Niño, which commenced in early 1997 and was stronger than any observed so far (stronger than even the 1982-1983 event, which was stronger till then), made no dent in the 1997 March-May rainfall in northeast Brazil or the June-September Indian summer monsoon rainfalls in 1997, mainly because of the stronger influences of other factors. Yet the El Niño saga continues, because that is sensational news. Ironically, the El

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