Characteristics of Low-Frequency Sea Surface Temperature Fluctuations in the Tropical Atlantic*

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ABSTRACT

Sea surface temperature anomalies in the tropical Atlantic Ocean are reexamined to investigate an apparent low-frequency oscillation that has been described as a fluctuating dipole structure with poles north and south of the equator and a node near the ITCZ. Using principal components rotated by the varimax method and simple correlations of area-averaged temperatures, we show that during the 1964–88 interval SST anomalies north and south of the ITCZ are not significantly correlated. Therefore, the low-frequency variation, with an apparent decadal period observed in the SST gradient across the ITCZ during 1964–88, does not arise from temporally coherent and out-of-phase fluctuations in each hemisphere and cannot be characterized as a dipole.

1. Introduction

Many recent studies have revealed large-scale coherent patterns of low-frequency sea surface temperature (SST) fluctuations in the tropical Atlantic. For instance, the analysis of composite SST fields associated with extreme rainfall anomalies in the Sahel (Lamb 1978a,b) or Northeast Brazil (Hastenrath and Heller 1977) suggests a pattern of SST anomalies with opposite sign north and south of the intertropical convergence zone (ITCZ). Correlation calculations (Moura and Shukla 1981) between the SST anomalies, using the deviation from a 25-year mean from 1948 to 1972, and Northeast Brazilian rainfall anomalies show a region centered near 10°S, 10°W with a positive correlation exceeding 0.6, and a comparable region centered at 15°N, 45°W with a negative correlation exceeding −0.4, which are significant at the 95% confidence level. The sign change of this correlation roughly coincides with the locus of the ITCZ. Principal component (PC) analyses of SST anomaly fields (Weare 1977; Hastenrath 1978; Lough 1986; Semazzi et al. 1988; Servain 1991) produce a mode with loadings of opposite sign north and south of the ITCZ. These results have led to characterizing a significant portion of the low-frequency SST variance in the tropical Atlantic as a dipole with poles north and south of the ITCZ (Moura and Shukla 1981; Semazzi et al. 1988; Ward et al. 1988; Fontaine 1990). Since the annual cycle of SST fluctuations is dominantly dipolar in structure (Servain and Legler 1986; Houghton 1991) and is associated with the meridional displacements of the ITCZ, these results suggest that the interannual fluctuation might be a modulation of the annual cycle.

One source of uncertainty in this characterization concerns the properties of PC analysis, described by Horel (1981), reviewed in detail by Richman (1986), and illustrated by Richman and Lamb (1985), which may distort the structure of the variability and contribute to a misleading interpretation. This has to do particularly with the orthogonality condition imposed on the unrotated eigenfunctions of all but the first mode, which can result in higher modes that have a predictable geometric relationship to the first mode. For example, if the first unrotated mode has the same sign throughout the domain, the second unrotated mode is likely to be a dipole with a node passing through the region where mode 1 has the maximum value. Since this is the pattern seen in the aforementioned tropical Atlantic SST eigenfunctions, it seems useful to extend the analysis using rotated PCs for which the orthogonality restraint is removed from the spatial structure to see if the dipole pattern is robust. In this note we present the results of such an analysis with PCs rotated by the varimax method (Kaiser 1958). Similar calculations have been presented by Nicholson and Nyenzi (1990) as part of an analysis of SST in the tropical Atlantic and Indian oceans, although its implications for the SST fluctuations across the ITCZ were not developed. We shall show that SST fluctuations

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north and south of the ITCZ are uncorrelated in time and, although the sign of the meridional SST gradient across the ITCZ undergoes low-frequency fluctuations, these do not arise from a regime that can be characterized as a simple dipole.

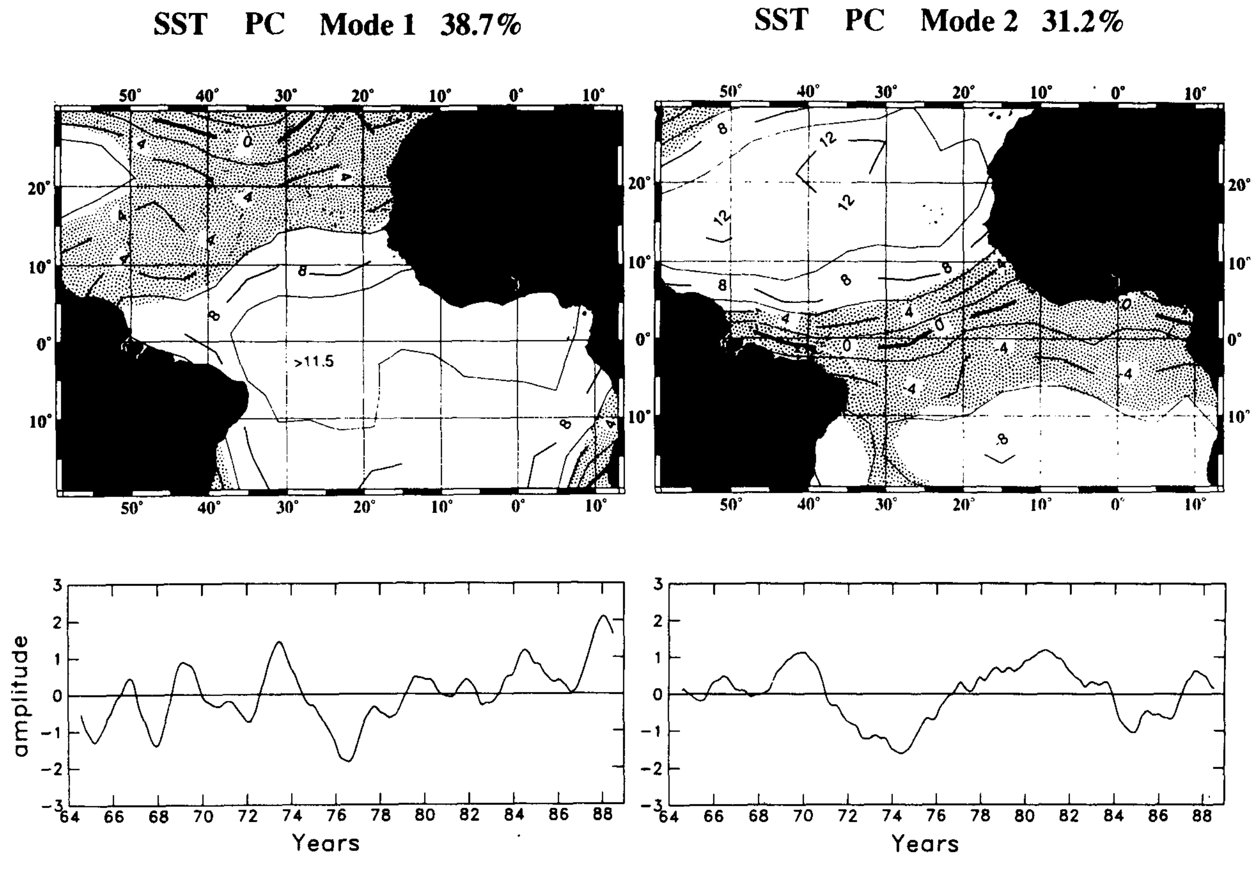
2. Data

The data used in this study are the SST compiled by J. Servain from merchant ship observations between 1964 and 1988 in the region 30°N–20°S, 60°W–12°E in the tropical Atlantic and are described in Picaut et al. (1985) and Servain et al. (1987). The monthly SST anomalies are derived from the record-long monthly means and normalized by the monthly standard deviation. The original 2 × 2° latitude–longitude grid was reconfigured to a 4 × 4 grid, then filtered with a 13-month running mean.

3. Principal component analysis

The first two unrotated time-domain PCs are shown in Fig. 1. Since the three subsequent modes account for 8%, 4%, and 3.5% of total variance, respectively, the first two modes with 38.7% and 31.2% of the variance, respectively, are clearly dominant. The structure of the eigenvectors is consistent with previous analyses, such as Weare (1977), Hastenrath (1978), Lough (1986), Semazzi et al. (1988), and Servain (1991). The first mode has a maximum at the equator and no sign change throughout the domain. The second mode has extrema of opposite sign off the equator with a node slightly north of the equator near the mean position of the ITCZ. It is this structure that has been characterized as a dipole, although we note that the amplitude of the northern pole is larger. The eigenvector structure at both poles is significant at the 95% level for the approximately 25 degrees of freedom in the data. The time dependence of this mode is predominantly low frequency with an almost decadal period, distinctly lower than the first mode whose higher-frequency fluctuation appears to contain a quasi-biennial oscillation.

The first two unrotated PC modes easily satisfy the Preisendorfer and Barnett (1977) "N rule" for statistical significance. However, we note that their eigenvalues have nearly the same magnitude. Therefore, there is a possibility that sampling error could result


SST PC Mode 1 38.7%

SST PC Mode 2 31.2%

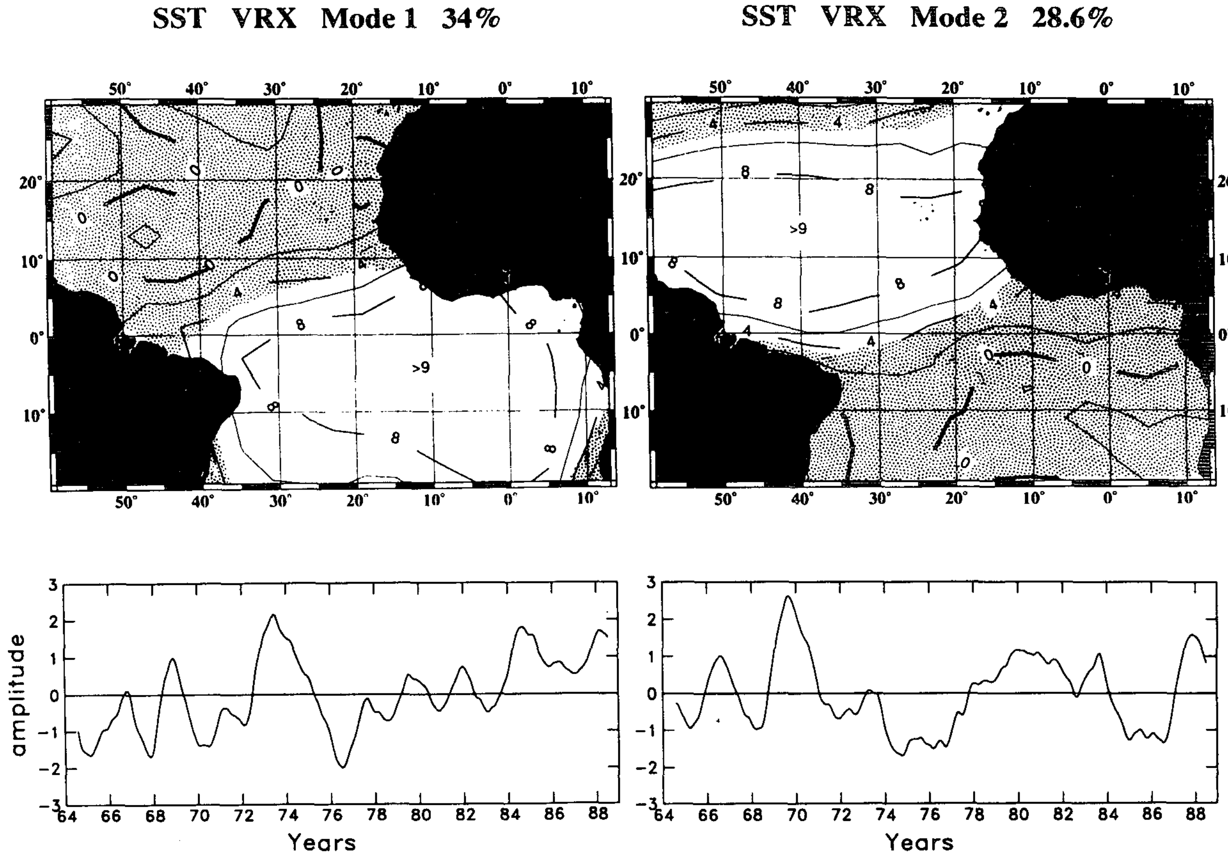
FIG. 1. Unrotated PC modes 1 and 2 from 25 years of SST anomalies on a 4 × 4 degree grid in the tropical Atlantic Ocean. Loadings are multiplied by 10. Amplitude is in units of standard deviation (~0.43°C). Stippled area indicates where mode is not statistically significant at the 95% confidence level.

in a degeneracy such that the calculated eigenvectors are not unique but linear combinations of other eigenvectors. The sampling error for an eigenvalue λ is given by North et al. (1982) to be $\lambda(2/N)^{1/2}$ where N is the number of degrees of freedom. From the data decorrelation time of approximately 1 year, N is 25, so the sampling error is 10.9 and 8.7 for modes 1 and 2, respectively. Since the separation of the two eigenvalues is only 7.5, the possibility of degeneracy and effective mixing of the modes exists. Degeneracy may also be a problem for previous analyses, especially those of Weare (1977) and Semazzi et al. (1988).

To test the robustness of the PC eigenvectors and to see whether the dipole pattern of the second mode is domain dependent, we perform an orthogonal rotation of the PC modes using the varimax method (Kaiser 1958; Richman 1986). By maximizing the variance (second moment) of the squared loadings, unrotated PCs maximize the sum or first moment, the spatial structure of the rotated PCs becomes more spatially localized, and the variance at each grid point is projected onto fewer modes. Using the scree test (Cattel 1966) to determine the appropriate truncation, we rotate the first five PC modes, which incorporates 85% of the total variance. Increasing this to seven produces no appreciable change in the structure of the first two rotated modes. The first two rotated SST modes explaining 34% and 28% variance are shown in Fig. 2. These are the two dominant modes; mode 3 explains less than 10% of the variance.

The first two rotated SST modes are discernibly different from their unrotated counterparts. For mode 1 the maximum amplitude is now centered near 5°S between 0° and 30°W. Mode 2 is nearly a mirror image with maximum amplitude near 10°N between 30° and 50°W. Both modes have weak extrema of the opposite sign in the other hemisphere, but these are not statistically significant. As expected, the rotation produced modes that are more separated spatially, but the dipole structure that was prominent in unrotated mode 2 is now not statistically significant. Since the rotated modes are by definition orthogonal in time, these results indicate that most of the low-frequency variance in the SST anomaly field north and south of the ITCZ is not correlated at a zero time lag.

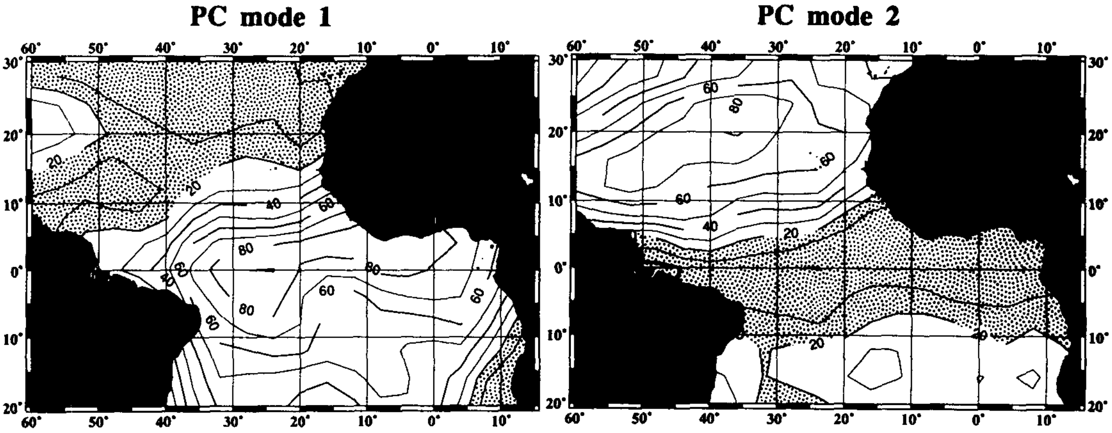
The spatial separation produced by the varimax rotation is illustrated more clearly in plots of the variance explained, that is, the squared correlation between the PC mode and the original data, shown in Figs. 3a,b. Here given approximately 25 degrees of freedom in the


SST VRX Mode 1 34%

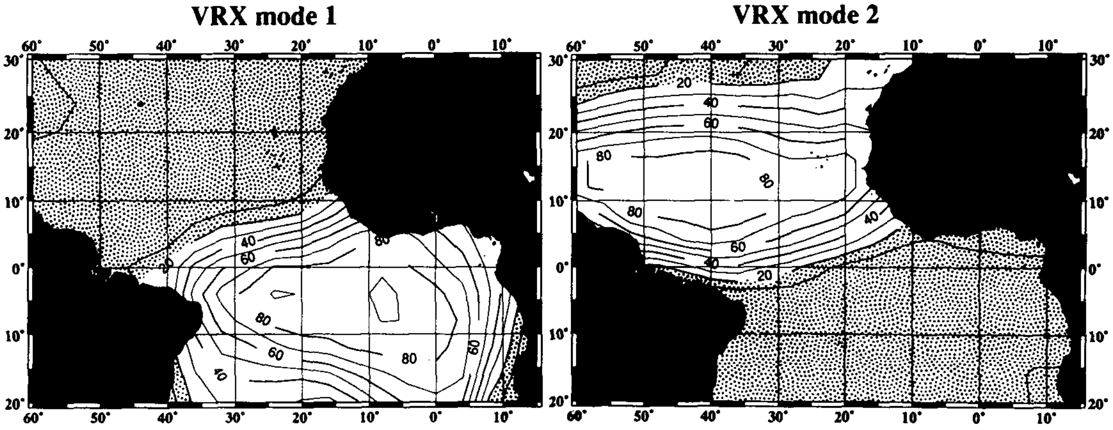
SST VRX Mode 2 28.6%

FIG. 2. As in Fig. 1 but for modes 1 and 2 derived from a varimax rotation of the first five PC modes.

a) % VARIANCE EXPLAINED



b) % VARIANCE EXPLAINED



c) T Correlation

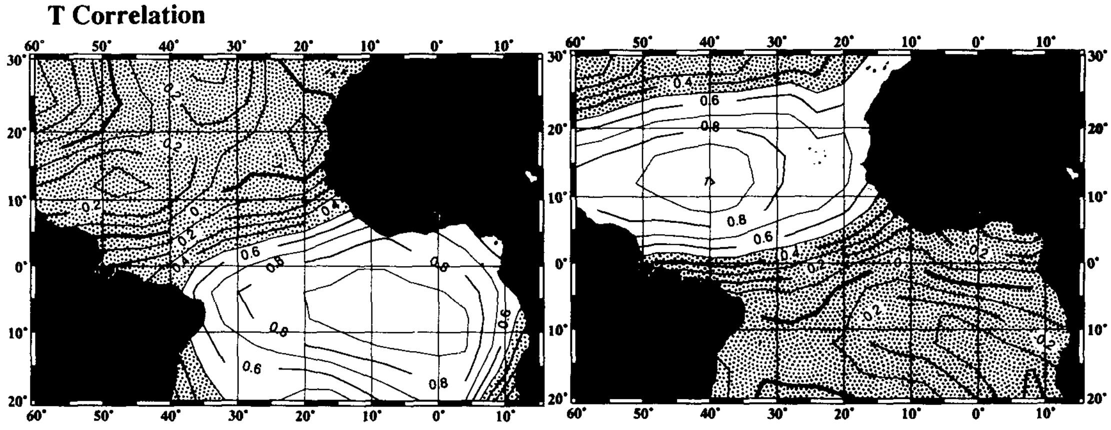


FIG. 3. (a) Percent of SST variance explained by unrotated PC modes 1 and 2. (b) Percent of SST variance explained by varimax rotated modes 1 and 2. (c) Point correlation map of SST with respect to 7°S, 7°W (left) and 13°N, 39°W (right). Stippling indicates areas not statistically significant at the 95% confidence level.

data, the 20% isopleth denotes the region where the modal structure is statistically significant at the 95% confidence level. The domains of the first two modes that originally overlapped become separate and distinct when rotated. The southern pole of the "dipole" in mode 2 becomes statistically insignificant. In none of the higher rotated modes (not shown) is there a dipole with centers near 20°S and 20°N.

Several questions are suggested by this result. Is there evidence of SST fluctuations with a dipole structure in the original data? If it existed, would a dipole structure be projected onto a single varimax mode? To see if there is any indication of a dipole structure in the original data we construct a point correlation map—that is, the correlation between one grid point and successively with all the other grid points in the domain. For the two maps shown in Fig. 3c, we chose the grid point closest to the center of rotated modes 1 and 2; that is, 13°N, 39°W and 7°S, 7°W. The calculations show that for the SST record at 13°N, 39°W the maximum correlation anywhere on the opposite side of the ITCZ is only ~ −0.3, which is not significant at the 95% confidence level (~0.4). Squaring the correlation coefficient produces a map of the variance explained that is consistent with that of the varimax modes including even the feature in the southeast corner of mode 2 in Fig. 3b. There are examples of rotated PC calculations, such as Northern Hemisphere atmospheric pressure anomalies produced by Kushnir and Wallace (1989), wherein a single rotated PC mode has statistically significant loadings of opposite sign. Therefore, we conclude that the structure produced by the rotated PC modes is an accurate representation of the data and that if a statistically significant dipole existed it would be incorporated into a single mode.

Since the first two rotated modes effectively partition the tropical Atlantic SST variance into two distinct domains separated at the ITCZ, we further test our conclusions by dividing the original data similarly into two parts. Within these regions separated by 3°N from Brazil to 13°W and then 7°N to the west African coast we calculate an area-mean temperature using the normalized SST anomalies. The resulting time series, designated north (N) and south (S) and shown in Fig. 4, are virtually identical with the time dependence of the rotated PC modes 1 and 2, respectively, as expected. The zero lag cross-correlation of these two time series is 0.1, which is not significantly different from zero. It is interesting to note that the time series of the sum (N + S) is similar to the unrotated PC mode 1, and the difference (N − S) is very similar to the unrotated PC mode 2. Using the same dataset, Servain (1991) has presented results of a similar calculation where the line separating the north and south region is 5°N and the time series are not lowpass filtered. The time series designated as N, S, N + S, and N − S in Fig. 4 are thus virtually equivalent to the time series designated by Servain (1991) as NB, SB, TB, and dipole index, respectively.

4. Conclusions

We have shown that the orthogonal rotation by the varimax method alters the PC eigenfunctions of the anomaly SST in the tropical Atlantic Ocean sufficiently to suggest a reinterpretation. Instead of two modes, one with an antinode near the equator and a second, a dipole, with a node near the ITCZ, we find two dominant modes that are spatially separated by the ITCZ. Since time series associated with these modes accounts for more than 80% of the variance over large regions centered at 15°N, 40°W and 55°N, 10°W, they represent most of the spatially coherent variance over the central tropical Atlantic. Since these modes by definition are orthogonal in time, most of the low-frequency variance north and south of the ITCZ is uncorrelated. Simpler calculations using point correlations of the original data confirm that the rotated modes are an accurate representation of the data, and that there does not exist any correlated variance with a dipole structure across the ITCZ that is statistically significant at the 95% level. Our results also indicate that the first two unrotated modes may indeed be degenerate as suggested by the sampling error estimated in the previous section. The degenerate PC modes may actually be linear combinations of other independent modes. In our case, Fig. 4 shows that unrotated modes

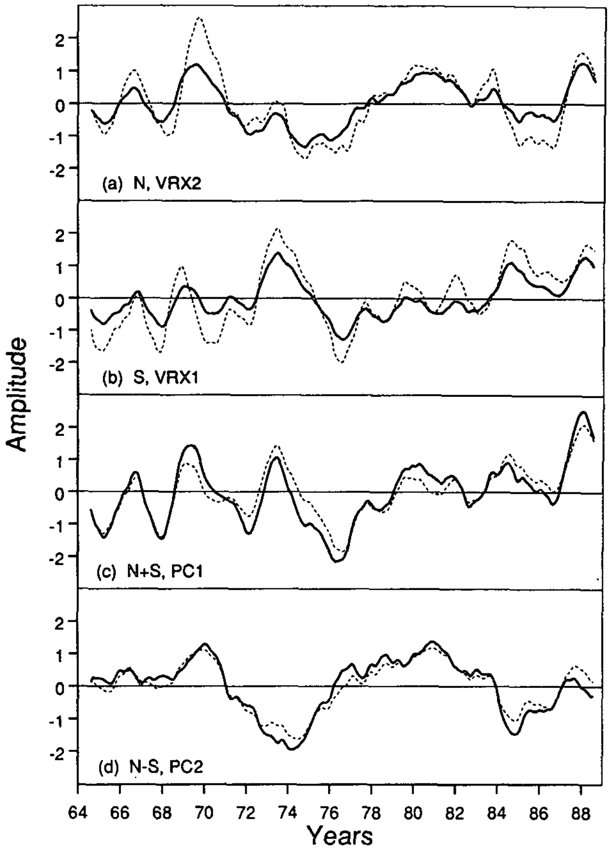


FIG. 4. Time series of the area-mean temperature, as described in the text, (bold line) and for comparison a corresponding principal component (dashed line): (a) north and rotated mode 2; (b) south and rotated mode 1; (c) north + south and unrotated mode 1; and (d) north–south and unrotated mode 2. Amplitude in units of standard deviation.

1 and 2 are approximately the sum and difference of rotated PC modes 1 and 2.

The low-frequency fluctuation in the north–south temperature difference, derived from both the unrotated PC analysis and a simple spatial average, is certainly real. However, to characterize this difference as a "dipole index" (Servain 1991) is an incomplete description since the fluctuations at each pole are not correlated. An example of a dipole index would be the Southern Oscillation index (SOI) used to characterize the fluctuating sea level pressure field over the Pacific Ocean. The SOI is a difference of two normalized sea level pressure anomaly time series that are significantly negatively correlated at zero time lag. The pressure field can thus be considered to be a fluctuating dipole or a seesaw. In contrast, the Atlantic SST dipole index is the difference of two uncorrelated time series. The approximately decadal time scale observed for this index during 1964–89 would then not be an inherent time scale of the entire tropical Atlantic system since the decadal fluctuation appears to exist only for the SST anomalies to the north of the ITCZ (Fig. 4).

Our results are not incompatible with the correlation calculations of Moura and Shukla (1981), which show that high rainfall in Northeast Brazil is associated with warm (cold) SST south (north) of the ITCZ. Consider two uncorrelated time series $\mathrm{N}(t)$ and $\mathrm{S}(t)$ such that their time-average product $\langle \mathrm{N} \cdot \mathrm{S} \rangle = 0$. Now define a third time series $D(t) = \mathrm{N}(t) - \mathrm{S}(t)$. It is easily shown that $\langle D \cdot \mathrm{N} \rangle = \langle \mathrm{N}^2 \rangle$ and $\langle D \cdot \mathrm{S} \rangle = -\langle \mathrm{S}^2 \rangle$. We have constructed an example where two uncorrelated time series are correlated, with opposite sign, to a third. If, to some degree, the Northeast Brazilian rainfall were related to the north–south SST difference it would explain the observed rainfall–SST correlation. The same could be true of SST correlations with Sahelian rainfall.

From the many studies of the variability of tropical Atlantic SST through empirical orthogonal function (EOF) analysis or rainfall–SST correlation patterns, it has been inferred that there is a correlation in the SST anomalies across the ITCZ that can be characterized as "a north–south dipole pattern of SST anomalies" (Ward et al. 1988) or a "north–south seesaw anomaly pattern" (Semazzi et al. 1988). In a model calculation to describe the interannual variability of rainfall in the tropical Atlantic, Moura and Shukla (1981) explicitly use a diabatic heating function with this dipole structure to represent the thermodynamic forcing of the atmosphere by the ocean. It has been suggested (Philander 1986) that the interannual variability of the SST anomalies is related to anomalous meridional excursions of the ITCZ, which affect or reflect changes in the atmospheric circulation and ocean–atmosphere interaction on both sides. Since outside of the equatorial waveguide the SST in the tropical oceans appears to be primarily a function of surface flux (Bjerknes 1964; Seager et al. 1989; Liu and Gautier 1990; Houghton 1991), we might expect SST and wind anomalies north and south of the ITCZ to be coherent and out of phase. Our analysis shows that for broadband calculations over the time interval 1964–88 this is not the case; that is, temperature fluctuations north and south of the ITCZ are not correlated. Although during this time interval SST and local wind anomalies are correlated (Houghton 1991), we have found and will present in a subsequent paper that the low-frequency wind and surface atmospheric pressure anomalies across the ITCZ are uncorrelated. The correlation between the Atlantic SST and the Northeast Brazilian rainfall, which has a dipole pattern, could arise because the processes responsible for the precipitation are sensitive to the meridional temperature gradient or because they are different for the SST anomalies north and south of the ITCZ.

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