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Simple Climatic Indices for the Tropical Atlantic Ocean and Some Applications

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Two indices related to the sea surface temperature (SST) variability in the tropical Atlantic are proposed. One index describes the SST averaged over the whole basin (30°N to 20°S, 60°W to 15°E), and the other illustrates a meridional dipole between the northern and southern hemispheres. The computational method for obtaining these indices is intentionally kept simple, the objective being to reproduce the signature of the main results previously provided from more complicated statistical analyses. Monthly time series for both indices are produced from 1964 up to the present time. The whole basin index exhibits principally a sustained warming which has intensified since about 1975, and it has a significant periodicity close to that of the quasi-biennial oscillation. The dipole index exhibits a decadal-scale variation, and its building up seems to be related to other worldwide climatic changes, as for instance El Niño / Southern Oscillation extreme episodes, rainfall variabilities over the Brazilian Nordeste and African Sahel.

1. INTRODUCTION

Indices calculated from atmospheric or oceanic data can provide a useful technique for describing climatic variability. A well-known example is the difference between the sea level pressures at Tahiti and Darwin, which is widely used as an index of the Southern Oscillation (SO). Until now, several indices have been proposed for the tropical Atlantic region. Generally, the studies were adapted to specific cases. For example, *Hastenrath et al.* [1984] and *Hastenrath* [1990] developed a method, based on indices of anomalies in the large-scale circulation, that permits one to forecast more than half of the interannual rainfall variability of the Brazilian Nordeste. *Wright* [1986, 1987] discussed an index that represents sea surface temperature (SST) anomalies in the Atlantic Ocean centered over the Gulf of Guinea and compared it with precipitation events over North Africa and El Niño occurrences.

A basic aim of this note is to propose indices which provide simple measures of the climate variation in the tropical Atlantic region. Because of the large correlation between tropical oceanic and atmospheric circulations, our indices are based upon SST analyses. They are derived from simple calculations.

2. THE MAIN MODES OF INTERANNUAL SST VARIABILITY OVER THE TROPICAL ATLANTIC

The amplitude of interannual climatic variability with respect to the seasonal signal differs widely between the tropical Pacific and Atlantic oceans. This is particularly evident for SST. Interannual SST perturbations are strongest in the tropical Pacific Ocean, especially during El Niño episodes. In contrast, the annual cycle of SST dominates in the Atlantic [*Merle et al.*, 1980; *Hastenrath*, 1984]. This strong signal results mainly from seasonal upwellings in the eastern part of the basin. However, it has been established that anomalous deviations from the annual cycle could persist, even in the tropical Atlantic for more than 1 year [*Servain et al.*, 1985].

Diagnostic investigations [e.g., *Hastenrath and Heller*, 1977; *Lamb*, 1978*a*; *Servain*, 1985] or statistical studies principally using analyses of empirical orthogonal functions [e.g., *Weare*, 1977; *Hastenrath*, 1978; *Lough*, 1986; *Servain and Legler*, 1986] suggest that there are two main modes of SST interannual variability in the tropical Atlantic. Each of these modes accounts for about 20% of the variance of the monthly SST anomaly data base [*Déqué and Servain*, 1989]. Loading patterns, resulting from a recent analysis [*Braud*, 1990], are represented in Figure 1. The first mode describes a warming (or a cooling) trend in most of the basin; the associated amplitude time series (not shown) indicates a long-term temperature trend in the tropical Atlantic Ocean. The second mode exhibits an asymmetrical structure about the equator. Variations of this thermal dipole are connected with anomalous meridional displacements of the kinematic axis separating northern and southern hemisphere trades [*Lamb*, 1978*b*; *Servain*, 1985], 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. It has been demonstrated that the mode of interannual Atlantic SST variability described by the meridional dipole is associated with rainfall anomalies both in the African Sahel [e.g., *Lamb*, 1978*a*,*b*] and the Brazilian Nordeste [e.g., *Hastenrath and Heller*, 1977; *Moura and Shukla*, 1981]. Moreover, the Atlantic SST dipole is related to the tropospheric circulations over the northern hemisphere [*Déqué and Servain*, 1989] and the Southern Oscillation [*Covey and Hastenrath*, 1978; *Hastenrath and Wu*, 1982; *Hastenrath et al.*, 1987].

3. THE DATA

The data base is formed from monthly averaged SST from 1964 up to the present on a 2° X 2° grid. The study area (Figure 2) extends from 30°N to 20°S and from 60°W to the African coast. Raw data originate from ships of opportunity and are obtained from the National Climatic Data Center (NCDC) and from the National Meteorological Center (NMC). The 1964-1989 SST monthly maps and details of the data processing can be found in three sequential atlases [*Picaut et al.*, 1985; *Servain et al.*, 1987; *Servain and Lukas*, 1990].

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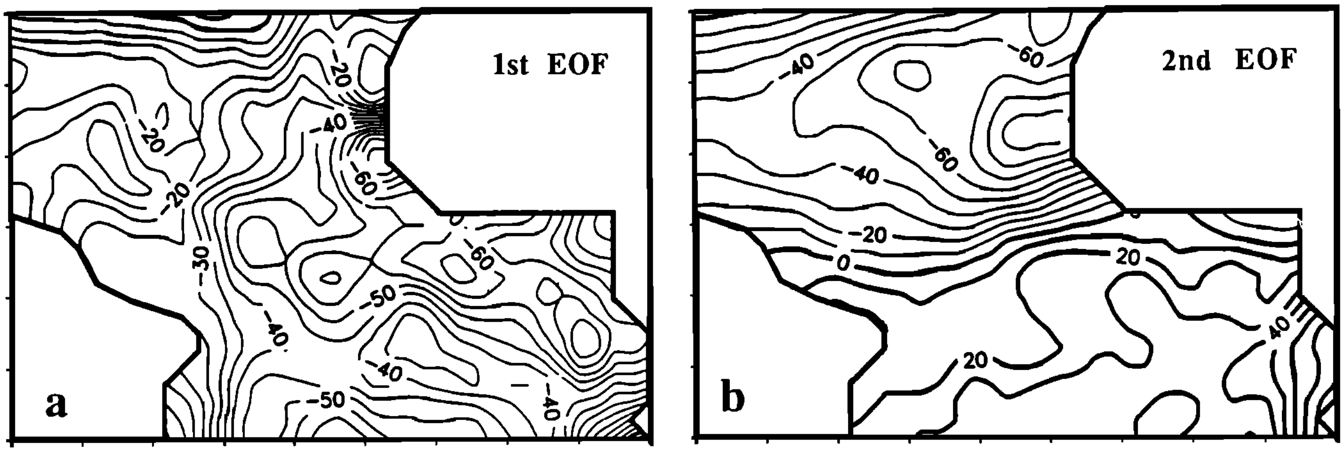


Fig. 1. (*a*) First and (*b*) second EOF loadings (in units of 1/100°C) computed from Servain's 1984-1987 monthly SST data set. (Adapted from *Braud* [1990].)

4. A SINGLE INDEX FOR THE WHOLE TROPICAL ATLANTIC

The whole tropical Atlantic Ocean basin, hereinafter referred to as TB, is defined when using the total area from 30°N to 20°S. Integrated over TB and computed from the years 1964-1990, the total long-term average of SST is 25.35°C; its mean annual cycle varies slightly from a maximum of 25.69°C in April to a minimum of 25.05°C in August, indicating a weak preponderance of the southern over the northern hemisphere. A time series of monthly SST anomaly is compiled by removing the mean annual signal. The 12 monthly SST standard deviations are given in Table 1; note that they all are close to 0.25°C. Dividing the anomalies by the standard deviations for each calendar month, we display the monthly standardized values of SST for TB from 1964 up to the present. Such a time series is presented here (Figure 3) as a single index of SST over the whole tropical Atlantic Ocean. The noticeable linear warming trend which occurred during the last 3 decades (up to 0.30°C) agrees with previous worldwide climatic studies [e.g., *Jones et al.*, 1986]. The range of this warming trend is particularly substantial since the mid-1970s. Before that time, cold events lasting many months followed similary long-lasting warm events. Episodes of very large SST anomalies (near 3 standard deviations) developed in the whole tropical Atlantic basin during 1969 and 1987 (warm) and during 1976 (cold).

A spectral analysis (not shown) performed from the TB index time series exhibits a significant periodic signal close to 26 months. Such marked preference for climatic variations around 2 years in the tropical Atlantic was previously noted [*Hastenrath and Kaczmarczyk*, 1981; *Chu*, 1984]. *Yasunari* [1989] suggested some relationship between tropical SST and the quasi-biennial oscillation (QBO) in the stratospheric zonal

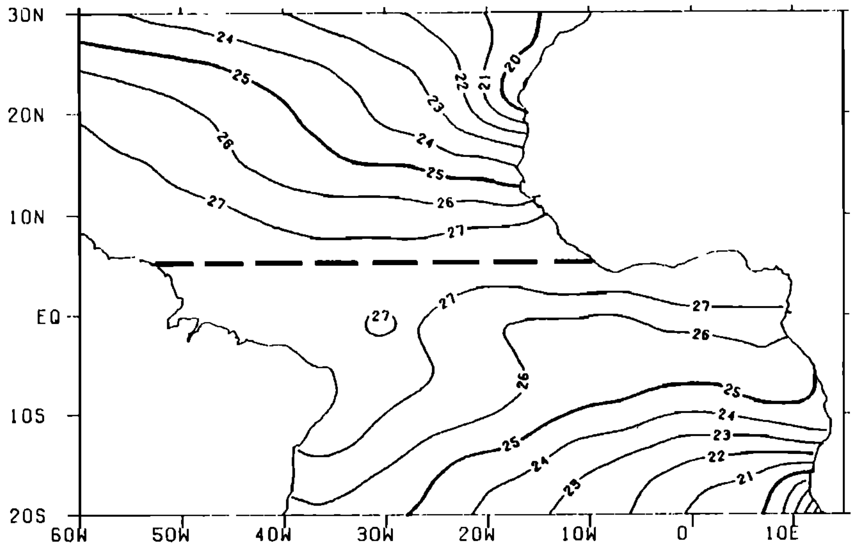


Fig. 2. Total average (1964-1989) of monthly SST (in °C) over the tropical Atlantic basin. The broken line at 5°N represents approximately the climatic latitude of the thermal equator. (Adapted from *Servain and Lukas* [1990].)

TABLE 1. Monthly Standard Deviation of QBO, TB, NB, and SB

Month	QBO, Knots*	TB, °C	NB, °C	SB, °C
Jan.	24.53	0.23	0.31	0.29
Feb.	25.05	0.23	0.33	0.29
March	22.99	0.25	0.41	0.31
April	25.48	0.26	0.44	0.29
May	21.28	0.25	0.41	0.30
June	19.71	0.26	0.34	0.36
July	18.99	0.24	0.29	0.35
Aug.	21.36	0.26	0.29	0.35
Sept.	23.08	0.24	0.24	0.34
Oct.	23.42	0.24	0.22	0.36
Nov.	23.86	0.23	0.24	0.33
Dec.	23.98	0.27	0.31	0.34

* One Knot equals 0.514 m/s.

wind velocity in the equatorial region. Computed during the same study period (1964-1990), the periodicity of the standardized QBO at Balboa (9°N, 80°W) is about 29 months. Because of the relative small length of the time series (N = 324), this 29-month QBO peak is not significatly different from the 26-month TB peak. Note, however, that this disaccord in period is evident in that the two times series do not fluctuate in phase throughout the full record (Figure 3).

5. AN INDEX FOR THE ATLANTIC THERMAL DIPOLE

A measure of the meteorological equator is the zone of maximum SST. This domain migrates meridionally in the course of the year. Its northern and southern limits are reached at the end of each extreme season, that is, in March and September, respectively [*Hastenrath and Lamb*, 1977; *Servain and Lukas*, 1990]. For the Atlantic Ocean the meridional shift of the warm waters is generally a little larger in the western (from 10°N to 5°S) than in the eastern (from 12°N to 0°) part of the basin. However, averaged over the year and all longitudes, latitude 5°N can be regarded as a suitable representation of the thermal equator; it will be used here to demarcate the northern and southern basins, hereinafter referred to as NB and SB, respectively (Figure 2). The southern limit of SB is that of our data set (20°S). The northern limit of NB is taken to be 28°N, rather than 30°N, in order to preserve an equilibrium between the annual thermal changes of both hemispheric basins.

The two 27-year time series of monthly SST values, spatially averaged in NB and SB, are represented in Figure 4. The total long-term averages are very close: 25.54°C and 25.58°C for NB and SB, respectively. The plots exhibit a strong annual signal with a mean range close to 3°C. The two annual oscillations are not exactly out of phase: while NB is coldest in February-March (24.14°C) and warmest in September-October (26.95°C), SB is warmest in March-April (27.20°C) and coldest in August-September (24.02°C). Nevertheless, the durations of the intermediate seasons are identical for both hemispheric domains: about 7 months are necessary to run from the cold to the warm season, and 5 months are required to come back from the warm to the cold season.

In spite of the strong annual signal it is possible to discern some evidence of the interannual variability of NB and SB thermal rate. For instance, the NB generally sustained warming trends at the end of the last 3 decades and cooling trends during their middle years (Figure 4*a*). Recently, *Citeau et al.* [1989] and *Servain et al.* [1990] discussed a linear warming trend which has been occurring over the southern part of the tropical Atlantic since at least the mid-1960s. This warming trend is particularly evident during the austral winter (August-September), and it can be seen in Figure 4*b* as a decrease of about 0.7°C in the severity of the cold season since the 1960s. The intensity of the warm season in SB varies also but without

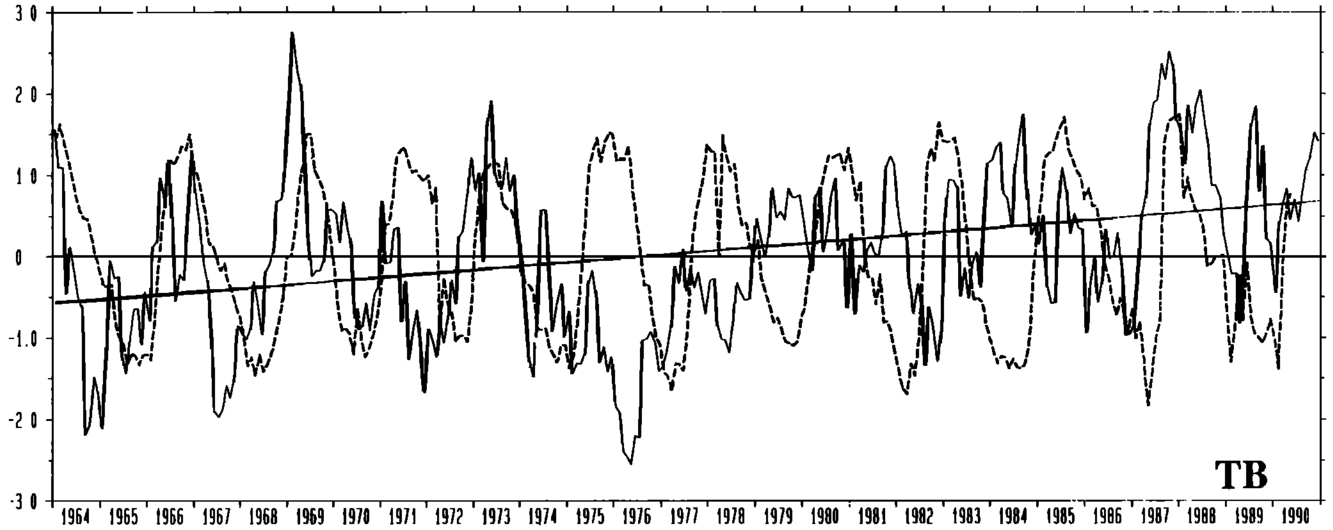


Fig. 3. Time series of monthly TB (solid curve) and QBO (dashed curve) indices (in standard deviations) from 1964 to 1990. The original monthly time series of QBO (B. Gray, personal communication, 1990) represents the magnitude of the 30-KPa zonal wind at Balboa (east wind negative). The linear trend of TB is represented by a thin line.

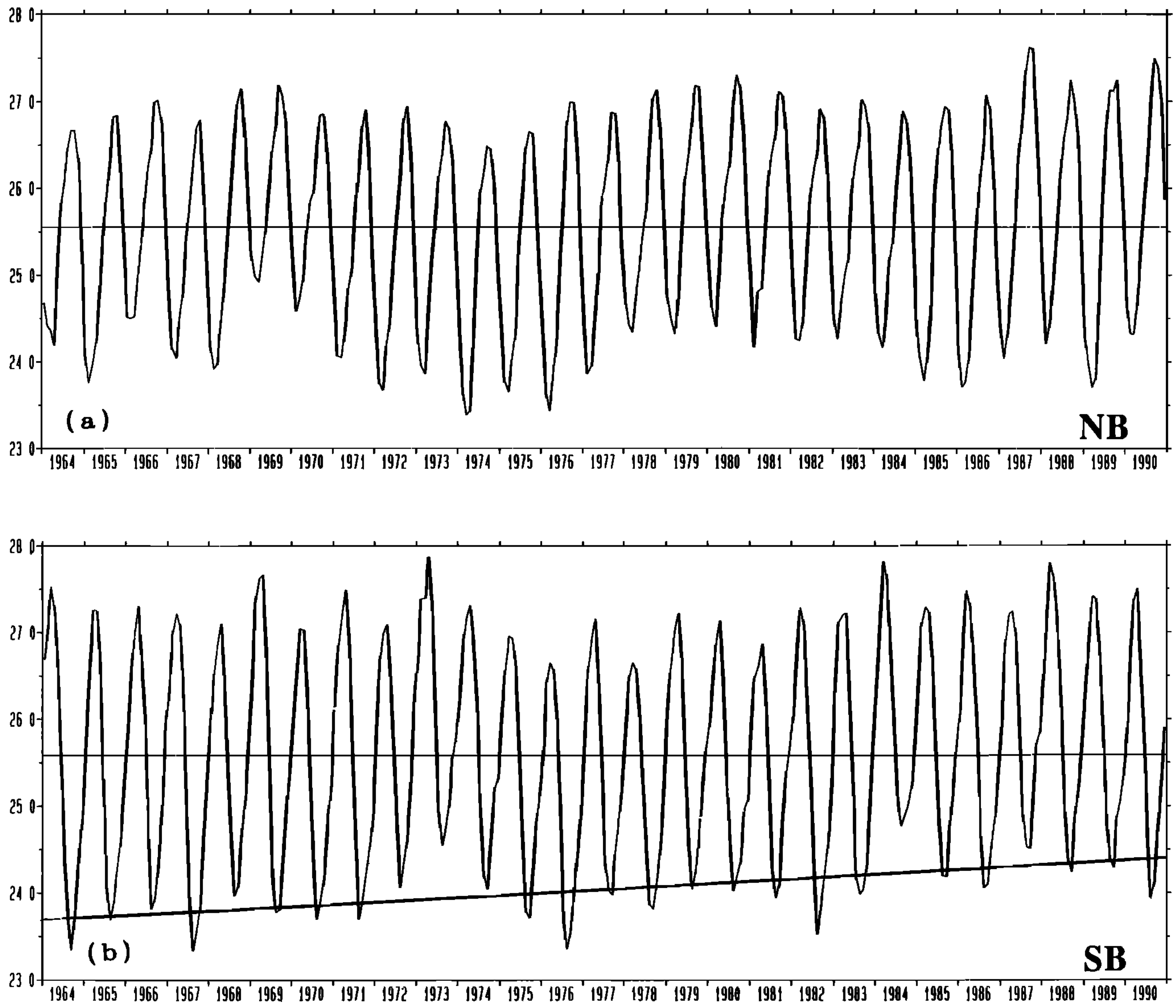


Fig. 4. Time series of the monthly SST (in °C) averaged (*a*) between 28°N and 5°N and (*b*) between 5°N and 20°S from 1964 to 1990. The linear trend of August-September SST averages in the southern area is represented by a thin line.

a noticeable regularity; we observe only that the warm season seems less prominent during the years 1974-1981.

Obviously, the interannual variability of SST in NB and SB is especially well documented by removing their mean annual cycles. As was previously done for TB, we computed the standardized monthly SST values for NB and SB from 1964 up to the present (Figure 5). The mean monthly values of standard deviations for NB and SB are reported in Table 1: they are near constant in the case of SB and are slightly dependent on the season in the case of NB. It is found for both NB and SB that abnormal climatic episodes reach or exceed 1 standard deviation during a few months, indeed a few years. A time-lagged cross-correlation analysis performed from the study period indicates that the relationship between NB and SB monthly time series is highest (r = -0.29) when SB leads NB by about 18 months, and is relatively weak (r = +0.23) at zero-month lag. Although such result implies that NB and SB indices do not fluctuate out of phase simultaneously, the time series of their difference discloses interesting characteristics. A positive (negative) value of the difference corresponds to an excess of the NB (SB) surface thermal energy relative to that of SB (NB). Computed over the years 1964-1990, the total range of this monthly index exceeds 6 standard deviations (Figure 6). The extremes were reached in December 1972 (-3.06) and March 1981 (+3.39).

The main feature, which clearly appears in Figure 6, is a slow variation of the dipole index on a decadal time scale. Indeed, the index was mainly positive during 1964-1970 and 1976-1983 but prevailingly negative during 1971-1975 and after 1984. This is broadly consistent with previous works [e.g., *Hastenrath and Kaczmarczyk*, 1981; *Folland et al.*, 1984; *Déqué and Servain*, 1989; *Druyan*, 1989].

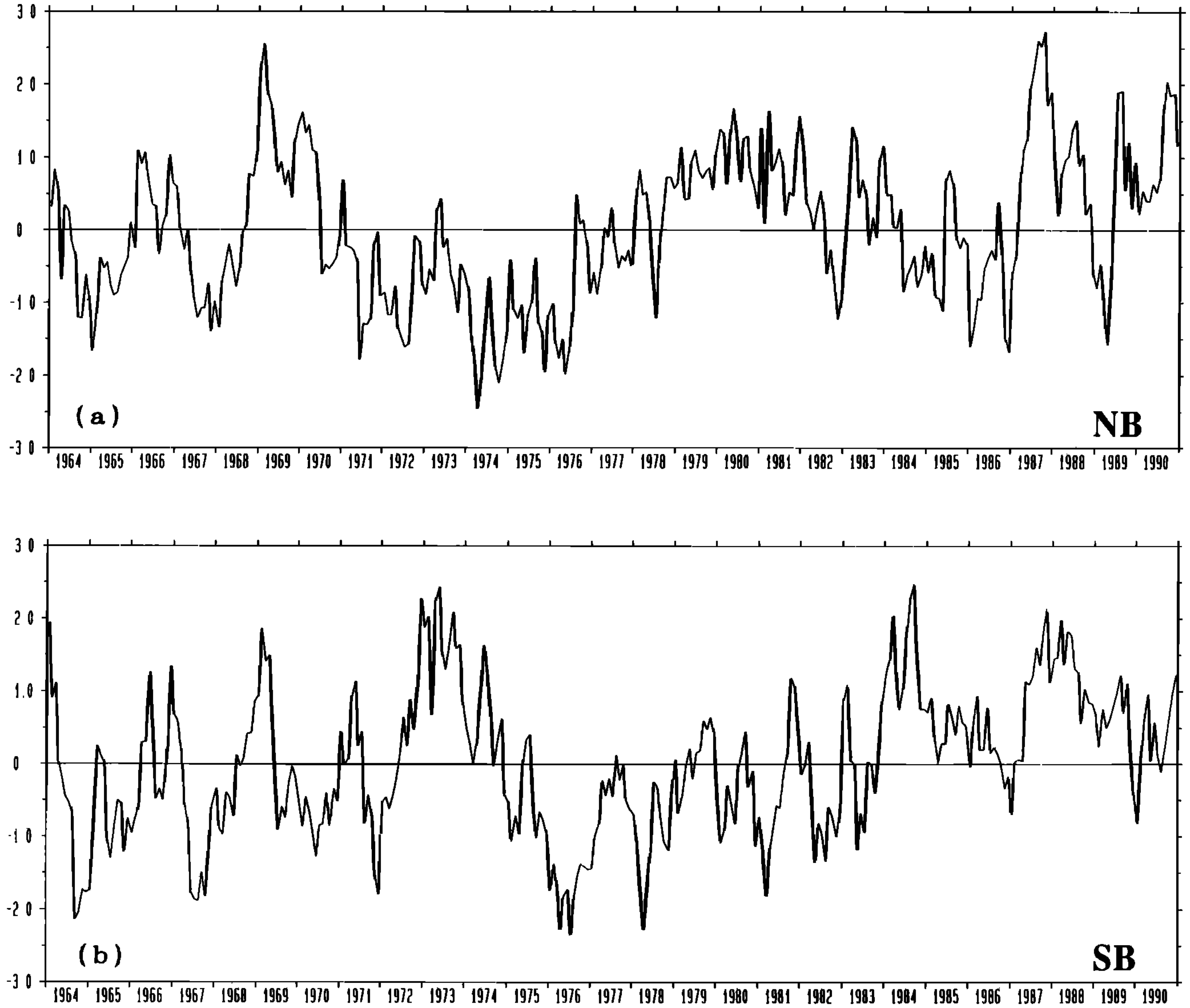


Fig. 5. Time series of monthly *(a)* NB and *(b)* SB indices (in standard deviations) from 1964 to 1990.

6. THE RELATIONSHIP BETWEEN THE ATLANTIC SST ANOMALIES AND OTHER CLIMATIC INDICES

The El Niño / Southern Oscillation (ENSO) phenomenon, which regularly appears immediately after Christmas over the tropical Indian and Pacific oceans [*Bjerknes*, 1969], is recognized as one of the major climatic events. The research of the teleconnections between the ENSO and other abnormal events is an important topic for a better understanding of the world climate fluctuations. Previous studies [*Covey and Hastenrath*, 1978; *Hastenrath and Wu*, 1982, *Hastenrath et al.*, 1987; *Déqué and Servain*, 1989] indicate that during El Niño (anti-El Niño) episodes, the northern tropical Atlantic is warm (cold) whereas the southern tropical Atlantic is rather cold (warm). Using the 1964-1990 monthly records, we performed time-lagged cross-correlation analyses (see Table 2) between our Atlantic SST indices defined in the previous sections (TB, NB, SB, dipole) and a time series of standardized values of ENSO; for convenience, we defined the ENSO index to be Darwin-minus-Tahiti atmospheric pressure, just the opposite from the usual definition, in order that equatorial Pacific SST anomalies and values of the ENSO index have the same sign. The correlation coefficient maxima are relatively weak (varying from 0.25 to 0.40), but these small values are not surprising if we take into consideration that fewer than 10 major "El Niño / anti-El Niño" occurrences were observed during the 324 months of the study period. Note that the ENSO index is less well correlated with the Atlantic dipole index than with any of the other Atlantic indices, implying that the climatic teleconnection between the Pacific and Atlantic Oceans is regulated by a more complex scheme than described by the previous studies mentioned just above. As we suggest later, such apparent inconsistency could result from the timing in the growth of the Atlantic dipole.

According to Table 2, the highest correlation coefficients between ENSO and SB are negative (about -0.30) and found when ENSO follows SB by about 2 seasons, whereas the

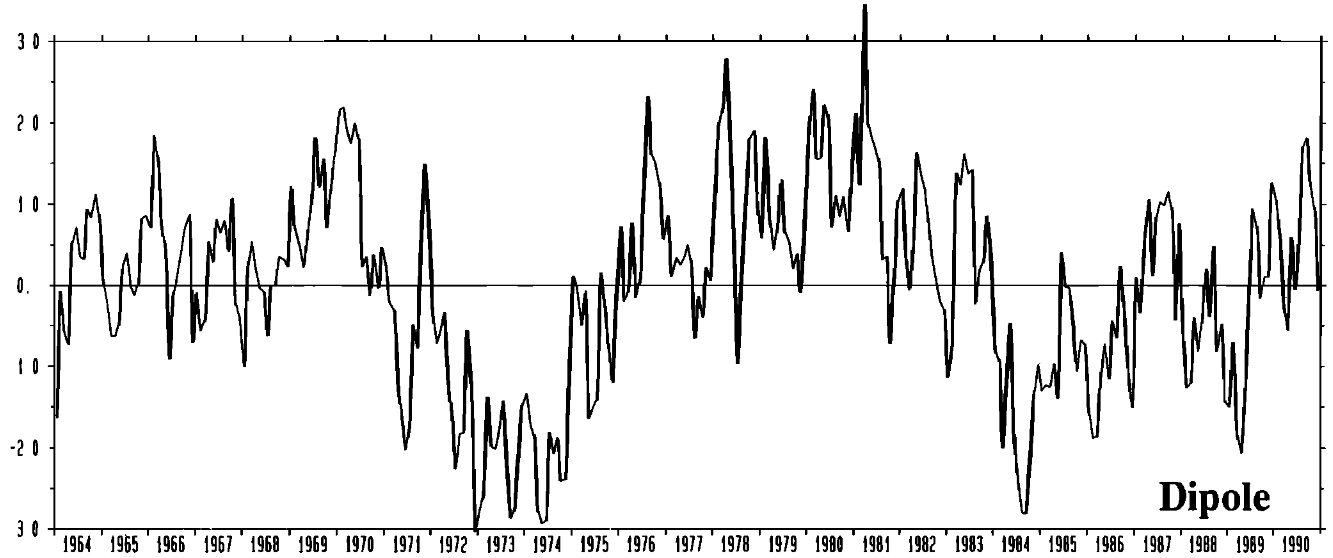


Fig. 6. Time series of the monthly dipole index (NB minus SB; in standard deviations) from 1964 to 1990.

highest correlation coefficients between ENSO and NB or TB are positive (up to +0.35) and found when ENSO leads NB by a few months or TB by about 1 year. These results can be summarized for an El Niño episode (with the inverse occurring for an anti-El Niño) as follows: relative 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 then observed in the north tropical Atlantic, and a few months later, the whole basin is finally warmer than normal. These results are consistent with earlier findings [*Covey and Hastenrath*, 1978; *Hastenrath and Wu*, 1982] and are further documented in the aforementioned atlases [*Picaut et al.*, 1985; *Servain et al.*, 1987; *Servain and Lukas*, 1990]. These Atlantic SST anomaly patterns are most pronounced for extreme ENSO events. To illustrate the empirical ENSO/NB relation, Figure 7 provides two opposite SST anomaly fields observed in the tropical Atlantic: the first one (strongly negative in the North) is the pattern in March-April 1974, a few month after the most extreme anti-El Niño recorded during 1964-1990, and the second one (strongly positive in the north) is the pattern in March-April 1983, just after the peak of the dramatic 1982-1983 El Niño. Similar computations (not shown) related to SB/ENSO and ENSO/TB empirical teleconnections exhibit positive (negative) SST anomaly patterns in the southern area during summer 1973 (1982) and negative (positive) SST anomaly patterns in nearly the entire basin during winter 1974-1975 (1983-1984).

Correlation analyses using calendar month values are informative regarding the aforementioned spatial associations. Here, relationships are discussed between our Atlantic indices and three other climatic indices, namely (1) the January-February averages of the previously discussed ENSO index, (2) an index (NORDESTE) of March-September rainfall anomalies in all Brazilian Nordeste prepared by S. Hastenrath (personal communication, 1991), and (3), an index (SAHEL) of April-October rainfall departures in West Africa proposed by P. Lamb (personal communication, 1988). Some examples of correlations computed between these yearly indices and the NB, SB, and NB-SB dipole indices are given in Table 3. The computations of the Atlantic indices are made for the extreme season months February and August. In particular, series are compiled in February for year *n* (FEB*n*), and August for year *n* (AUG*n*) or August for year *n*-1 (AUG*n*-1). Note that February corresponds to the beginning of the Nordeste rainy season and that August corresponds to the peak of the rainy season in the Sahel.

Of foremost interest in Table 3 is the relationships involving the Atlantic dipole. The ENSO index of January-February of year *n* correlates better (+0.44) with lagged NB(FEB*n*)-SB(AUG*n*-1) than with concurrent NB(FEB*n*)-SB(FEB*n*) Atlantic dipole (+0.21). NORDESTE correlates much more strongly (-0.65) with concurrent NB(FEB*n*)-SB(FEB*n*) dipole than with NB(FEB*n*) or SB(FEB*n*) separately. Similarly, SAHEL correlates more strongly with concurrent NB(AUG*n*)-SB(AUG*n*) dipole than with NB(AUG*n*) or SB(AUG*n*) separately.

7. SUMMARY AND CONCLUSION

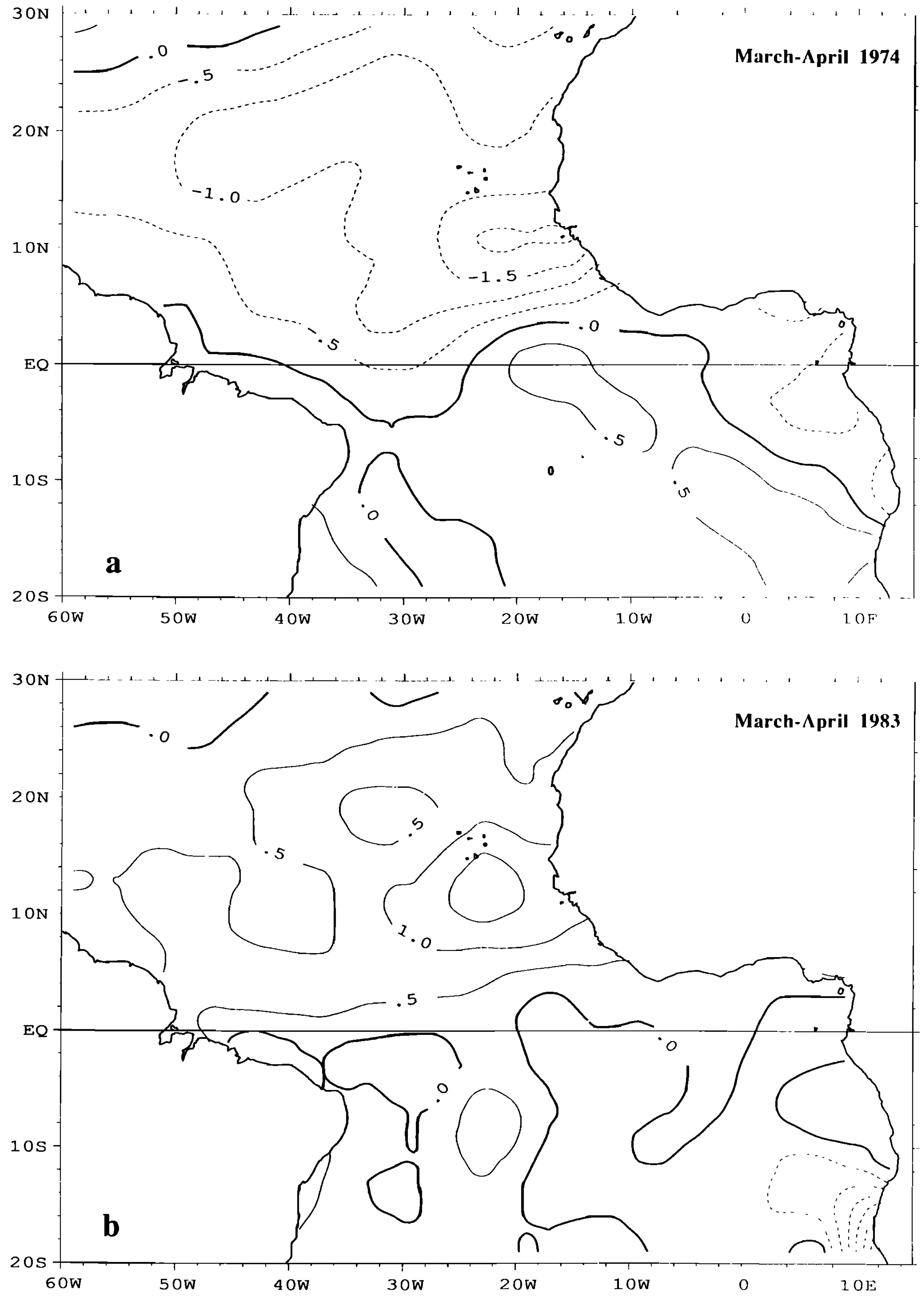
Two main modes of interannual climatic variability over the tropical Atlantic, similar to those found in previous studies, have been isolated: one is a basin-wide mode encompassing the entire basin, and the other is a meridional dipole mode straddling the meteorological equator. Each mode accounts for about 20% of the SST interannual variability. The two indices proposed here allow a synthetized view of these two SST anomaly patterns. The computational technique is to average standardized monthly SST anomalies inside tropical Atlantic areas. The first index is calculated by averaging over the Atlantic basin from 30°N to 20°S; the second index is obtained by averaging over the northern and southern tropical Atlantic basins (the line of separation being 5°N), and taking the difference between the two resulting values. Time series for both indices are computed from 1964 to 1990. The whole-basin index indicates a large warming of the tropical Atlantic Ocean, which has intensified since the mid-1970s. A significant periodicity at about 2 years appears in this index but may not be related to the QBO in the zonal winds of the equatorial stratosphere. The meridional dipole index varies mainly on the decadal time scale.

TABLE 2. Cross-Correlation Coefficients With Time Lag (From -18 Months up to +18 Months) Between the SO Time Series (Darwin - Tahiti) and Our Atlantic Index Time Series (Dipole, SB, NB, and TB)

Lag, Months	Dipole	SB	NB	TB
		ENSO Follows		
-18	0.16	-0.21	-0.02	-0.16
-17	0.15	-0.22	-0.03	-0.17
-16	0.12	-0.21	-0.06	-0.19
-15	0.12	-0.21	-0.06	-0.19
-14	0.14	-0.22	-0.05	-0.19
-13	0.15	-0.23	-0.04	-0.19
-12	0.15	-0.23	-0.04	-0.19
-11	0.18	**-0.26**	-0.04	-0.21
-10	0.18	**-0.25**	-0.04	-0.19
-9	0.20	**-0.29**	-0.03	-0.23
-8	0.23	**-0.29**	-0.01	-0.21
-7	0.24	**-0.30**	0.01	-0.21
-6	0.23	**-0.26**	0.02	-0.18
-5	0.21	-0.23	0.03	-0.15
-4	0.18	-0.20	0.02	-0.13
-3	0.17	-0.17	0.04	-0.10
-2	0.19	-0.14	0.09	-0.06
-1	0.22	-0.11	0.16	0.01
0	0.23	-0.04	0.24	0.11
		ENSO Leads		
1	**0.25**	0.01	**0.31**	0.19
2	**0.26**	0.03	**0.34**	0.22
3	0.24	0.05	**0.35**	0.24
4	0.24	0.09	**0.38**	**0.28**
5	0.23	0.11	**0.39**	**0.30**
6	0.20	0.14	**0.38**	**0.32**
7	0.16	0.18	**0.38**	**0.34**
8	0.15	0.20	**0.39**	**0.35**
9	0.15	0.22	**0.41**	**0.38**
10	0.15	0.20	**0.40**	**0.36**
11	0.09	0.24	**0.35**	**0.36**
12	0.03	**0.26**	**0.30**	**0.36**
13	-0.01	**0.26**	**0.25**	**0.33**
14	-0.03	**0.26**	0.22	**0.31**
15	-0.02	**0.26**	0.23	**0.31**
16	-0.04	0.24	0.19	**0.27**
17	-0.07	0.23	0.14	**0.25**
18	-0.10	0.23	0.09	0.22

The monthly time series are related to the years 1964-1990. The bold values are significant at 5% level.

The relationship between the Pacific ENSO phenomenon and the interannual SST anomalies in the Atlantic is also discussed on a monthly and yearly basis. Concurrent correlations computed between the ENSO index and the Atlantic SST dipole index are found lower than those computed between the ENSO index and each of the Atlantic basin SST indices. By contrast, the ENSO index correlates well with a lagged Atlantic dipole index (SB leading NB by a few months). This is in agreement with the fact that the northern and southern basins are out of phase with a time-lag of several months. It seems that an Atlantic SST dipole pattern grows progressively during the months surrounding the peak of an ENSO (or anti-ENSO) episode: weak cool SST anomalies appear in the southern Atlantic area a few months prior the peak, strong warm SST anomalies develop in the northern Atlantic area just after the peak, and these warm anomalies spread in the whole basin during the following months. Although this train of events has occurred during the main ENSO (or anti-ENSO) episodes of the last 3 decades, little is known about the actual processes that account for it; additional studies, including numerical modelling, will be needed to understand better the dynamics of the teleconnections between the two oceanic basins.



March-April 1974

March-April 1983

Fig. 7. Observed SST anomaly (in °C) averaged during *(a)* March-April 1974 and *(b)* March-April 1983.

TABLE 3 . Correlation Coefficients Between Calendar Month Values of NB, SB, and dipole (NB-SB) and (1) the 1964-1990 January-February values of ENSO Index (Darwin minus Tahiti), (2) the 1964-1987 NORDESTE Index, and (3) the 1964-1988 SAHEL Index

	ENSO(JAN*n*+FEB*n*)	NORDESTE(*n*)	SAHEL(*n*)
NB(FEB*n*)	**0.47**	**-0.44**	
SB(FEB*n*)	0.20	0.38	
NB(FEB*n*)-SB(FEB*n*)	0.21	**-0.65***	
NB(FEB*n*)-SB(AUG*n*-1)	**0.44**		
NB(AUG*n*)			0.14
SB(AUG*n*)			**-0.40**
NB(AUG*n*)-SB(AUG*n*)			**0.46**

The calendar month may be related to year *n* or year *n*-1. NORDESTE and SAHEL indices are defined in the text. the bold values are significant at the 5% level.

* Significant at 1% level.

The proposed dipole index relates particularly strongly to the concurrent anomalies in the Nordeste rainy season. It also exhibits some association with precipitation departures in the West African Sahel.

One recommendation from the third session of the Intergovernmental TOGA Board [*World Climate Research Program* (*WCRP*), 1990, p.24] was to "continue to examine... the ocean-atmosphere interactions in the tropical Atlantic, since these phenomena are clearly within the scope of TOGA." Because of the simplicity of our Atlantic indices, their values are easily computed in near real time. The complete 1964-1990 series of the dipole index described here has been published in the January 1991 issue of *Bulletin Océan Atlantique Tropical* (*BOAT*), which is an operaional product edited by TOGA-France. Updates will regularly appear in later issues.

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