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Climatology Comparison and Long-Term Variations of Sea Surface Temperature Over the Tropical Atlantic Ocean

JACQUES SERVAIN

Institut Français de Recherche Scientifique pour le Développement en Coopération,
Institut Français de Recherche pour l'Exploitation de la Mer, Plouzané, France

MARC SÉVA

Université de Bretagne Occidentale, Brest, France

PIERRE RUAL

Institut Français de Recherche Scientifique pour le Développement en Coopération
Nouméa, New Caledonia, West Pacific

The primary aim of the present study is to compare two sea surface temperature (SST) climatologies produced from merchant ship observations over the tropical Atlantic Ocean. The first climatology uses measurements taken between 1911 and 1972. The second uses 1964–1984 data. The second climatology is generally warmer by a few tenths of degrees. Part of the difference is due to changes in the temperature measurement techniques with time. The difference also shows, especially along shipping routes, some spatial discrepancies which are not due to instrument changes. It is demonstrated the difference is mostly caused by inhomogeneity in the spatial and temporal density of the available observations used to construct the first climatology. Using a simple technique to eliminate spurious bias, the analysis allows isolation of the long-term trend of SST anomalies in the tropical Atlantic Ocean during this century. South of the thermal equator, a warming trend occurs principally during boreal summers and extends to the present with an increasing range when calculated over the past 26-year period. In the north, such a warming is more questionable between the 1940s and 1970s. It is more evident during the past 26-year period but with a temperature range less than half of that for the southern basin. Thus large abnormal patterns have a tendency to straddle the thermal equator, including a north-south climate dipole. Three spatially limited areas with a cooling trend are suggested. The reliability of SST anomalies along the tropical section of the Europe–South America shipping track in recent years is also discussed.

1. INTRODUCTION

During the past few years, an increasing effort has been made to estimate recent interannual variability of the world climate. Most of the studies were based on analyses of air and sea surface temperature (SST) time series. Indeed, for data collected from the beginning of the present century, it is generally accepted [*Cayan*, 1980; *Paltridge and Woodruff*, 1981] that these two variables vary in harmony on time scales of more than a month. Because of heating of the ship superstructures during the daytime, the correlation is better when only using nightime marine air temperatures [*Folland et al.*, 1984; *Oort et al.*, 1987]. On a hemispheric scale, these authors and others [*Jones et al.*, 1982, 1986*a*, *b*; *Angell*, 1986] show that the southern hemisphere experienced sustained warming and is currently at its warmest level [*Jones*, 1988]. Northern hemisphere temperatures increased until 1930–1950, decreased during the 1960s, and increased again during the past 10 years. Regional-scale studies allow us to specify these climate changes. Since tropical oceans strongly affect global atmospheric circulation, they are particularly important to investigate. The purpose of the current 10-year program Tropical Ocean–Global Atmosphere (TOGA) is to observe and understand year-to-year climate variability. The El Niño–Southern Oscillation (ENSO) phenomenon, with its marine effect which occurs principally over the eastern equatorial Pacific Ocean, is undoubtedly the most noted and pronounced case of such a variability. Major ENSO events, such as that which developed during 1982–1983 [*Quiroz*, 1983], lead to massive zonal displacements of climatic conditions over the tropics, including the tropical Atlantic [*Horel et al.*, 1986].

Due to a meridional geometry of the Atlantic basin, substantial heat flow occurs between both hemispheres [*Stommel*, 1979] and can influence the world's climate. Moreover, the SST anomalies over the tropical Atlantic are not insignificant [*Servain et al.*, 1985; *Philander*, 1986], although the temperature range of the annual cycle is larger than that of interannual oscillations. One of the objectives of the joint French and U.S. Français Océan et Climat dans l'Atlantique Tropical/Seasonal Response of the Equatorial Atlantic (FOCAL/SEQUAL) was understanding and modeling the seasonal redistribution of heat in the tropical Atlantic. FOCAL/SEQUAL ran from mid-1982 to mid-1984. The SST fields observed during the FOCAL/SEQUAL period were compared with available historical long-term averages computed on 2° latitude by 2° longitude spatial grids. Two historical SST data sets were used for reference. The first one was produced by *Hastenrath and Lamb* [1977] (henceforth called HL), while the second one was performed by

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Picaut et al. [1985] and updated by *Servain et al.* [1987] (henceforth called PS). Previously, these data sets have been independently used to (1) gain insight into interannual variability over the tropical Atlantic domain [e.g., *Hastenrath*, 1978; *Hastenrath and Kaczmarczyk*, 1981; *Servain et al.*, 1982, 1985; *Servain and Legler*, 1986] and (2) establish any related climatic patterns between the tropical Atlantic basin and some adjacent domains such as the sub-Saharan region [*Lamb*, 1978*a*, *b*; *Servain and Séva*, 1987], northeast Brazil [*Hastenrath and Heller*, 1977; *Chu*, 1983; *Servain and Séva*, 1987], or the Atlantic mid-latitudes [*Déqué and Servain*, 1989]. The starting point of the present study was to look for discrepancies existing between HL and PS. For that purpose, we computed the thermal difference fields between the average monthly means (section 2). A surprising resultant pattern induced us to look further into the analysis techniques used to construct each SST data process (section 3). The fact that HL and PS climatologies are built from different temporal samples allowed us to comment on the global long-term trend of SST inside the tropical Atlantic basin for the past 70 years (section 4). The paper concludes with a discussion of interpretations of SST variability along the tropical section of the Europe–South America shipping route during FOCAL/SEQUAL (section 5).

2. PS VERSUS HL CLIMATOLOGY

The raw data used for the construction of PS and HL climatologies were historical merchant ship observations achieved at the U.S. National Climatic Data Center, Asheville, North Carolina. Because of a greater international emphasis on obtaining ship reports, the number of observations increased suddenly after 1963. Thus the PS data file was derived from the well-documented 21 years, 1964–1984. A data set of about two million SST observations was used in the study area limited in latitude by 30°N and 20°S, in longitude by 60°W and the coasts of South America and West Africa. The sequence of processing steps is detailed by *Picaut et al.* [1985] and *Servain et al.* [1987]. The raw data were initially compiled and validated in 5° longitude by 2° latitude boxes for each month. Then the authors used a combination of both subjective and objective (based on *Cressman*'s [1959] method) analyses in order to produce monthly regular fields on a 2° square mesh. At every stage of these analyses, the number of available observations inside each individual box (2° × 5°) was taken into account and used to weight the computed monthly means. The average of the 252 individual months (21 years) of SST appears in Figure 1*a*. Hereafter this annual mean will be regarded as the PS climatology.

Full details of the construction of the HL data file are provided by *Hastenrath and Lamb* [1977]. Ship observations over the tropical Atlantic Ocean between 30°N and 30°S were processed in 1° latitude by 1° longitude squares. For each calendar month and individual 1° × 1° square box, Hastenrath and Lamb averaged the data over the entire 1911–1972 period, each individual observation having equal weight. The average of these 12 monthly SST fields (smoothed on a 2° × 2° mesh) appears in Figure 1*b* using the same geographic limits as for the PS climatology. Henceforth in our paper, this 62-year average will be regarded as the HL climatology.

In order to emphasize some points of our analysis, particularly to assess long-term trends, we have also used another version of HL climatology kindly provided by Hastenrath. It is based on SST monthly fields averaged over 5° squares from January 1911 to December 1972. In this second version (hereafter called HL5) the number of SST observations used to construct each monthly mean is available in each 5° square box. A data set of 2.8 million SST samples over the study area for the years 1911–1972 was used.

It is well know that an unfortunate problem with SST data derived from merchant ship observations is the changes in observation techniques over the years. The principal modification concerns a gradual change from bucket samplings to engine-intake measurements. According to *Folland et al.* [1984], noninsulated bucket temperatures dominated the reports before World War II. Intake measurements started around the beginning of the 1940s, while insulated bucket temperatures progressively took the place of noninsulated data. Estimates of the systematic errors induced by the use of the different techniques have been made. Insulated bucket temperatures probably have no bias. It is thought [*Folland et al.*, 1984; *Barnett*, 1984] that the effect of evaporation during measurements of SST with a noninsulated bucket can cause a temperature drop of up to 0.3°C. Moreover, some reports of temperature derived from intake measurements can be higher than their true magnitude, essentially due to the poor exposure of the thermometer to the water flow [*Saur*, 1963]. According to early works, the temperature difference between noninsulated bucket and intake techniques can vary from 0.3°C [*James and Fox*, 1972; *Tabata*, 1978] to 0.7°C [*Saur*, 1963]. Because of other external factors which lead to a further reduction in temperature of the recent observations (e.g., a deeper level of measurements induced by a gradual increase in the size of the ships of opportunity over the years), a 0.3–0.4°C positive bias in favor of the intake measurements is now generally recognized [*Folland et al.*, 1984; *Barnett*, 1984].

Unfortunately, there is no information about the observation technique used to take each historical measurement. Employing a systematic adjustment in these circumstances would yield questionable improvements. Moreover, the simple method promoted by *Folland et al.* [1984] and used by *Oort et al.* [1987] to correct the basic SST by nighttime marine air temperatures has not been made (they avoid daytime marine air temperatures because of solar heating of the ship structure). Therefore no correction has been applied when constructing the HL or the PS climatologies.

We have calculated the difference between the time-averaged fields PS − HL for each individual 2° × 2° box and mapped the result in Figure 2. For most of the study area this difference is positive, corresponding to a warmer PS than HL climatology. Because of the instrumental bias discussed previously, such a conclusion is not surprising, since PS (related to the 1964–1984 data base) is globally more recent than HL (related to the 1911–1972 data base). However, the range of the warming does not seem independent of location; larger positive differences (>0.2°C) tend to occur along the shipping lines, particularly between 20°N and 20°S along the Europe–South America track, where the two climatologies differ by more than 0.6°C in some limited areas. Another region of the above temperature difference (up to 0.4°C) is found along the African coast, approximately between the locations of Dakar and Abidjan. By contrast, in three small areas, the first one close to the Amazon River mouth, and

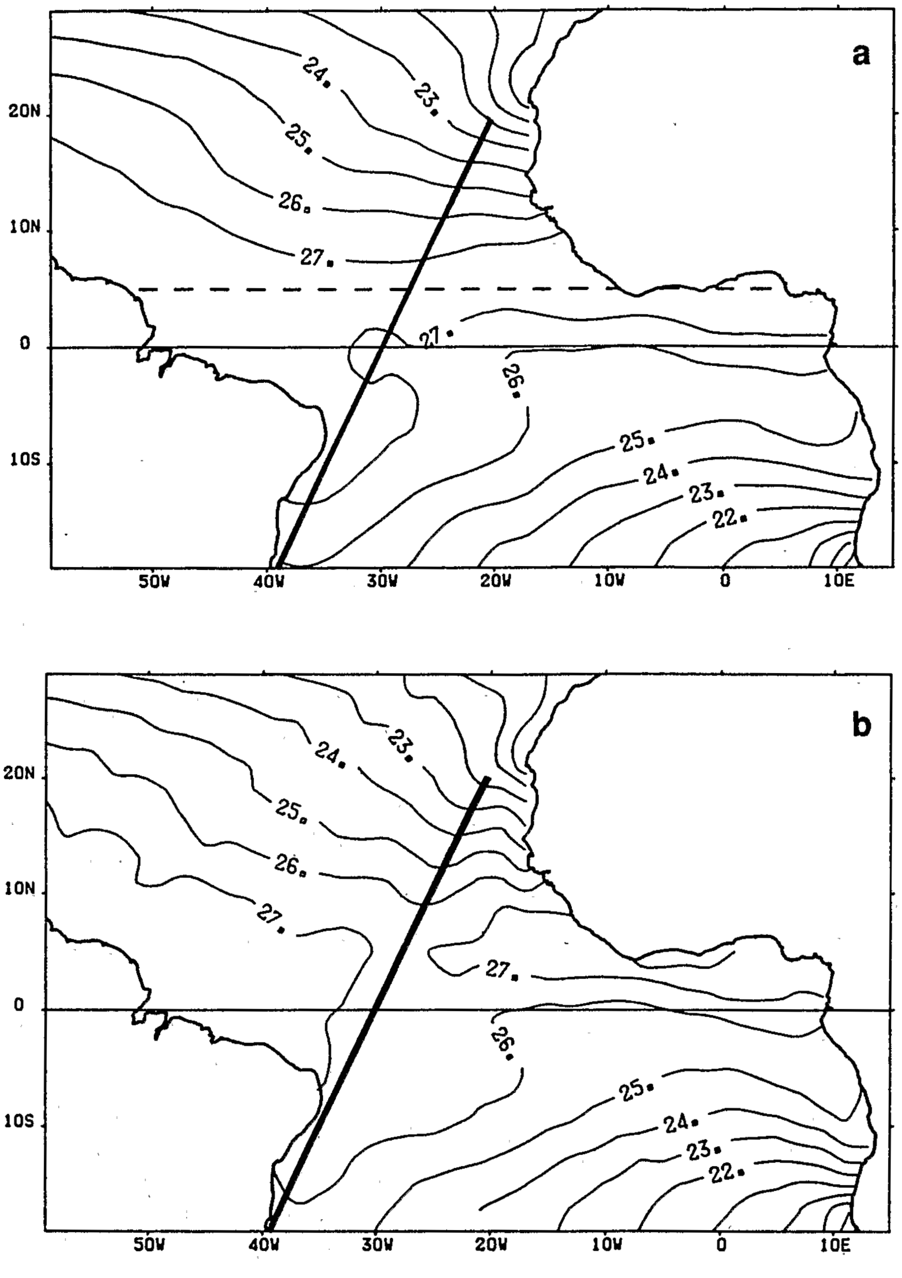

Fig. 1. (*a*) The PS climatology. Average (in degrees Celsius) of the 12-month SST climatology derived from *Servain et al.* [1987]. The broken line at 5°N represents approximately the climatic latitude of the thermal equator. (*b*) The HL climatology. Average (in degrees Celsius) of the 12-month SST climatology derived from *Hastenrath and Lamb* [1977]. The spatial grid is 2° longitude by 2° latitude in both cases. The thick line represents the Europe–South America shipping route between 20°N and 20°S.

the other two located in the vicinity of Mauritania and Angola coastal upwellings, respectively, PS is slightly colder than HL. This indicates that another bias, independent of the one introduced by the difference in observing techniques, exists between the two climatologies. Furthermore, if any climatic change occurred between the time periods related to each climatology, such a variation should have been displayed by the difference PS − HL. We shall investigate these questions in the following sections.

3. SPATIAL AND TEMPORAL ARRANGEMENTS OF THE HISTORICAL OBSERVATIONS

In order to understand the shipping line pattern observed in Figure 2, we need to consider in more detail the data processing of the two climatologies PS and HL. First, one point must be clarified. There is a possible mathematical effect introduced by weighting or not weighting the monthly means by the number of observations. We saw previously (section 2) that PS was constructed from monthly means which were weighted according to the number of the selected data, whereas HL was not weighted. In order to test that difference in the processing, we performed the following experiment. Using the HL5 data file, we completed two additional climatologies. The first was calculated according to a process similar to that used for building HL, i.e., for each calendar month, all the available SST monthly means were summed and then divided by the total number of available monthly means. The second was produced accord-

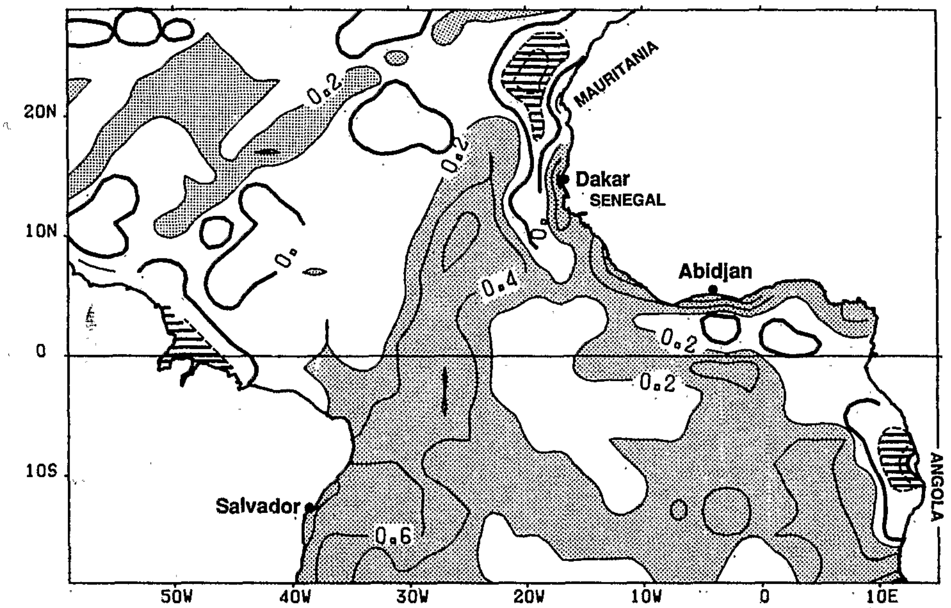

Fig. 2. Difference field (in degrees Celsius) between the PS climatology and the HL climatology. The stippled/hatched areas represent PS warmer/cooler than HL of > +0.2°C/< −0.2°C, respectively.

ing to a process similar to that used for the construction of PS, i.e., for each calendar month, all the available SST monthly means were summed, weighted by the number of selected observations, and finally divided by the total number of available observations. These two SST climatologies (not shown) are practically identical. Such a result seems to indicate that the major part of the dissimilarity noted previously between PS and HL (Figure 2) cannot be attributed to technological differences in the processes used in the construction of these climatologies.

To gain an insight into the explanation of the dissimilarity between PS and HL, we looked at discrepancies in the spatiotemporal density of the available observations inside the two data sets. A histogram of the total number of observations per month which have been selected to build the PS climatology is presented in Figure 3. Except for the first 7 months of 1971 and 3 months in mid-1974, the number of observations is large enough (>6000 per month) to provide reasonable monthly estimates of SST. To determine the spatial arrangement of the temporal distribution of the data, we made the following computation: the yearly number of observations in each 2° × 5° box between 1964 and 1984 were multiplied by the cardinal number of the year; the resulting number for each box was summed over the 21-year period; finally, that result was divided by the total number of observations in each box during the 21-year period. Thus we obtained a numerical field of one variable which could be called the "temporal center of gravity" (or "temporal barycenter"). This variable is plotted on Figure 4. Everywhere-close-to-1974 isolines indicate a strong spatiotemporal homogeneity of the PS climatology.

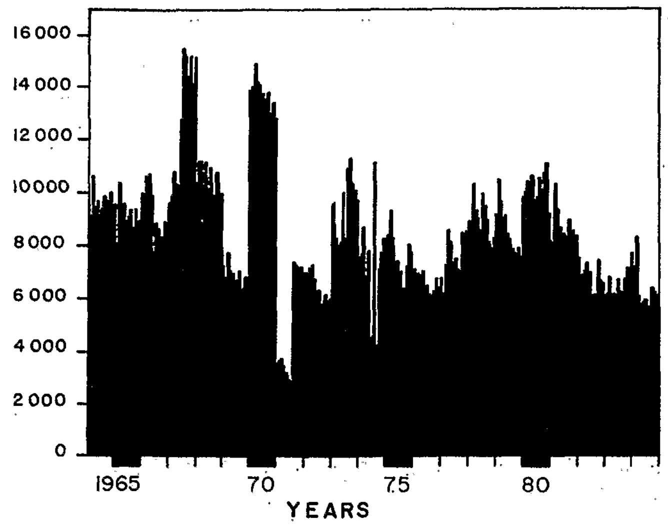

Fig. 3. Number of observations by month for the total study area for the PS climatology (1964–1984).

Figure 5 exhibits the monthly time series of the total number of selected observations which were used to produce the HL climatology. A large temporal inhomogeneity occurred throughout the years 1911–1972. As anticipated, the two periods included the world wars (1914–1920 and 1940–1946) were poorly documented (less than 2000 observations per month). By contrast, the years 1964–1969 were particularly well sampled (from 10,000 to 16,000 observations per month). During the two other periods, a short one in 1911–1913 and a longer one in 1922–1938, the number of observations was intermediate (from 3000 to 8000 observations per month). It is distressing to note that the available data during the 1947–1963 period were relatively few (from 2000 to 4000 observations per month). Finally, the very low number of data gathered in the HL climatology during 1970–1972 (less than 1000 observations per month) is due to the fact that the majority of the data during this period was not yet available when the analysis was constructed.

The temporal inhomogeneity is also high variable within the tropical basin. To illustrate this statement, we have selected four domains (Figure 6). Domains 1 and 4 contain the shipping lines Europe–South America and Europe-South Africa, respectively. Domain 2 is a poorly documented area

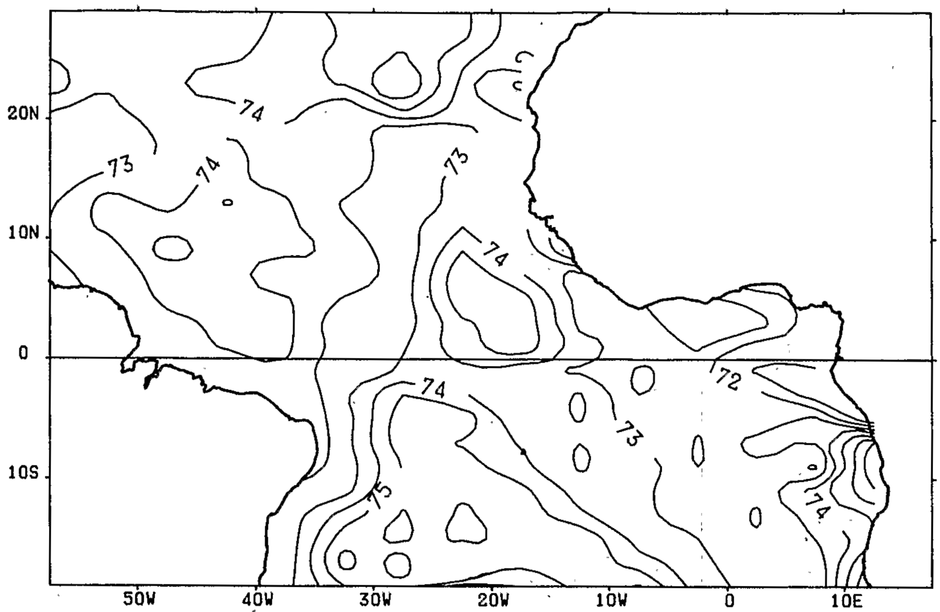

Fig. 4. The temporal center of gravity (in years of the present century) of the number of observations used to construct the PS climatology.

in the southern hemisphere and domain 3 is a relatively well documented area close to the Gulf of Mexico. The temporal sampling of domain 1 is very different from the temporal sampling of all the other selected domains (Figure 7). For the Europe–South America track, most of the data originated from the first part of the study period, i.e., before 1940. By contrast, in the other domains, most of the available data were derived from the second part of the study period (with the exception of the last three years 1970–1972). The inhomogeneity in the temporal density of observations is especially evident on domain 4 (the Europe–South Africa shipping line), since practically half of the total available information over 1911–1972 was based on only 6 years, 1964–1969. Figure 8 displays the temporal "centre of gravity" for the HL climatology. A large distortion in the field of this variable, in contrast with the PS case, confirms and enlarges what we discussed previously, viz., for the HL climatology, the Europe–South America ship track is mostly represented by data derived from years before 1940, in opposition to other areas, which are more related to years after 1950.

A comparison between patterns of HL temporal barycenter (Figure 8) and PS − HL difference (Figure 2) shows a strong correlation between the two maps, particularly along the Europe–South America shipping line. Therefore it seems that the other systematic bias introduced in the computation of the difference PS − HL (the first one being related to instrumental effect) results from a greater temporal inhomogeneity of the raw data which were used to construct the HL climatology. In the next section we will discuss correcting for these biases to reveal any true climatic change which occurred during the last decades in the tropical Atlantic Ocean.

4. Temporal Trend of SST Over the Tropical Atlantic Ocean

To attempt to remove the HL temporal inhomogeneity bias which appeared in the PS − HL difference computation, we proceeded as follows: for each grid point in the study area we divided the PS − HL difference (Figure 2) by the gap (in years) between the temporal centres of gravity (Figures 4–8) of the two climatologies. The result is the mean change in degrees per year for each 2° × 5° box. Figure 9 shows the spatial pattern of this trend in degrees per century. Our present purpose is only to approximate a temporal trend, keeping in mind the fact that the data of temporal range vary between 50 and 80 years only. In some places, the data before the World War II were so sparse that the trend is computed from a range of 30–40 years. Nevertheless, if we hypothesize that the rate of the climate modification was roughly the same during the 50 years centered about the middle of this century (such a hypothesis seems appropriate for air temperature at hemispheric scales, at least for the southern hemisphere; see Figure 1 of *Jones* [1988]), Figure 9 provides some interesting information on such a change. As shown in the difference between PS and HL (Figure 2), the

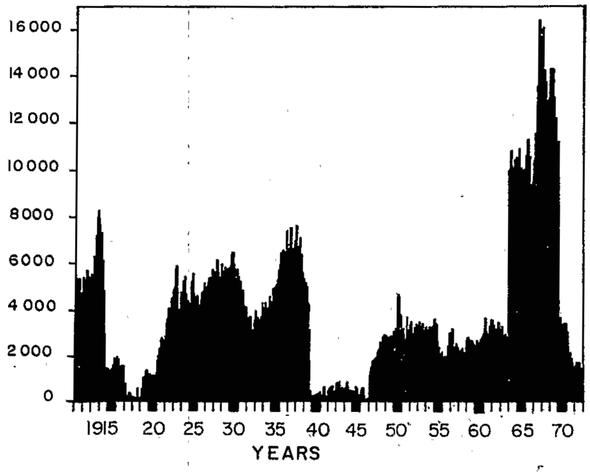

Fig. 5. Number of observations by month for the total study area for the HL climatology (1911–1972).

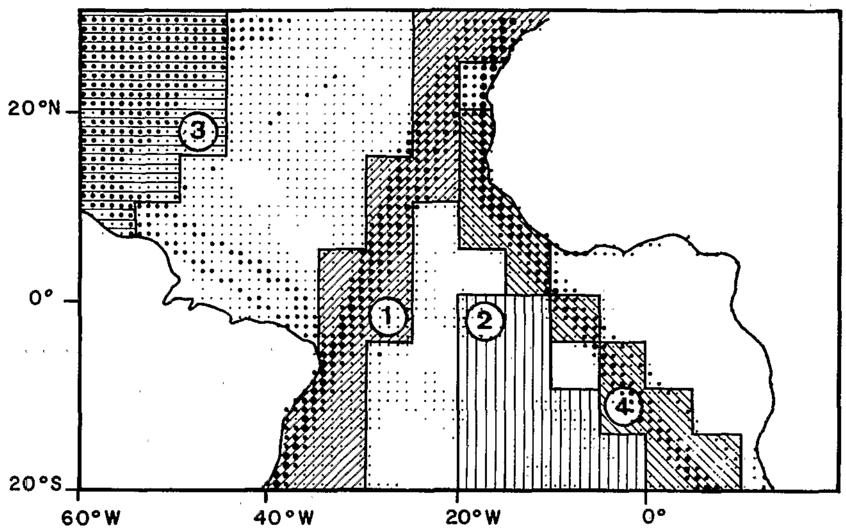

Fig. 6. Composite picture of the area coverage and the data density from *Hastenrath and Lamb* [1977]. Positions of the four domains are discussed in section 3.

rate of climatic change between both climatologies is a warming in nearly the whole tropical basin. However, in contrast to the crude difference pattern, which reproduced some bias at the same time due to the inhomogeneity in the HL data set distribution (in particular, the trace of the shipping lines), the pattern given in Figure 9 seems closer to a physical reality. Thus it appears that the warming was clearly more marked south of the thermal equator (a centennial value greater than 1.0°C) than to the north (a centennial value of about 0.5°C). Such a difference in the magnitude of the SST trend between the northern and the southern thermic hemisphere clearly discloses that instrumental bias is not the only cause of discrepancies between the two climatologies. Indeed, we cannot be certain of a long-term warming north of the thermal equator because of the relatively low magnitude of the trend displayed in this region. Thus, if we take into consideration the bias which could be induced by the instrumentation problem, i.e., if we add uniformly from the field of the HL climatology the bulk of a constant value close to a fraction of 0.3–0.4°C (see section 2), we could even identify an almost-zero pattern in the northern part of Figure 9. However, the larger values observed in the southern part, about 3–7 times the northern values, support the conclusion that warming in this region was real.

Our result is in agreement with previous papers based on the analysis of the air and/or sea temperature time series in both hemispheres [*Paltridge and Woodruff*, 1981; *Jones et al.*, 1982, 1986*a*, *b*; *Folland et al.*, 1984; *Cayan*, 1986; *Angell*, 1986; *Oort et al.*, 1987; *Jones*, 1988]. In particular, the difference in secular warming between the two hemispheres, already noted by these authors, could explain why the rate of the climatic change in the northern part of our study area is rather weak.

To estimate seasonal effects of these climatological discrepancies, we performed differences between PS and HL for each calendar month. The 12 patterns (not shown), whose average is the same as that shown in Figure 2, are similar and agree in sign. However, one phenomenon attracts our attention: when analyzing the monthly maps around August, the positive PS − HL values south (north) of the thermal equator are larger (smaller) in the range 0.1–0.2°C than for the average annual case. As a consequence, a north-south climatic difference (SST deviations close to zero in the north/warm SST in the south) strengthened principally during the end of boreal summers through the 1940–1970 period. Using an updated-to-1989 PS climatology, we looked at the recent development of the seasonal temperature tendencies. Similar to the previous decades, climatic trends are distinctively salient during the end of boreal summertime. As an example, Figure 10 represents the average for

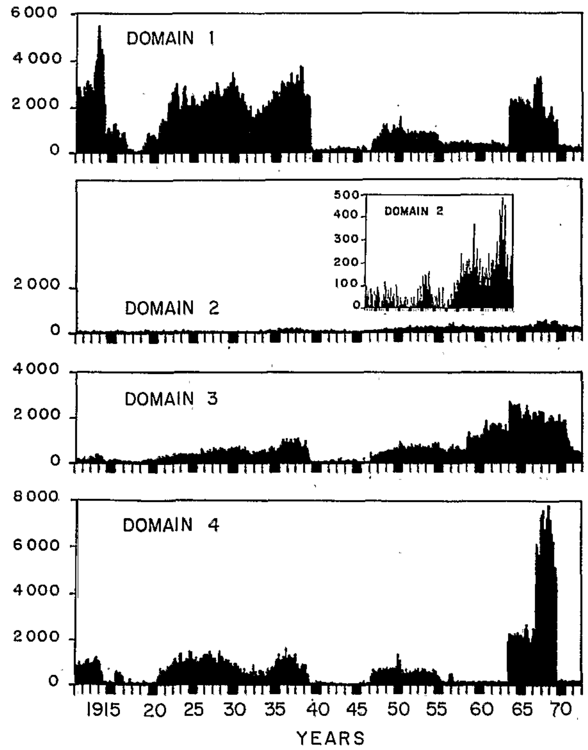

Fig. 7. Number of observations by month for each of the four domains demarcated in Figure 6 for the HL climatology (1911–1972). The scale of the vertical axis is the same for all the domains, but note also an enlargement of the vertical axis for domain 2.

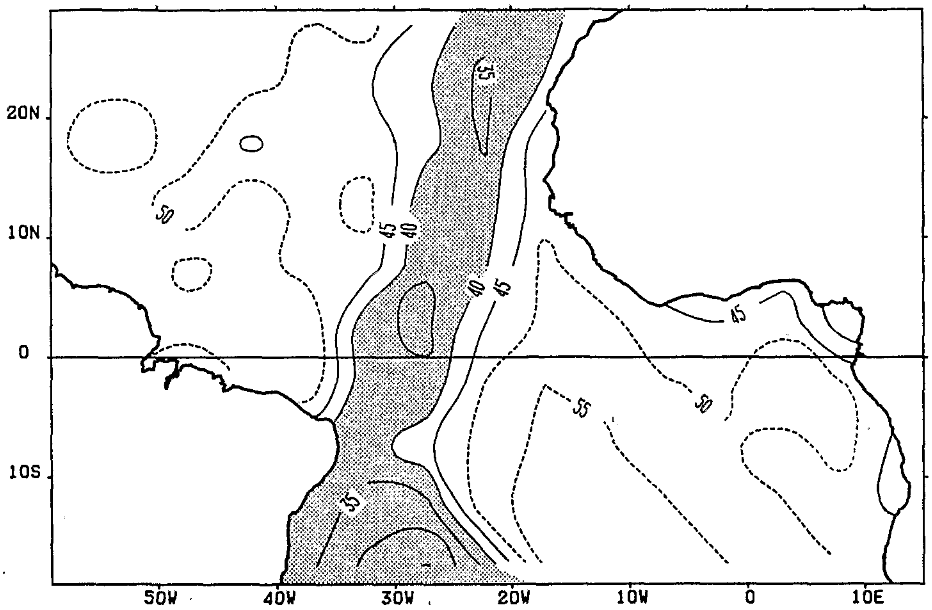

Fig. 8. The temporal center of gravity (in years of the present century) of the number of observations used to construct the HL climatology. Inside the stippled area the temporal center of gravity is before 1940.

August–September through the 1964–1989 period, of standardized SST anomalies spatially integrated over the whole oceanic study region south of 5°N (5°N can be regarded as the climatic latitude of the thermal equator; see Figure 1*a*). Adjusting the curve of Figure 10 by a linear function, the SST anomalies grew by 1.72 standard deviation during the past 26 years. The August–September standard deviation being of 0.35°C for that region, such a rise corresponds to a warming of about 0.6°C from 1964 to the present, i.e., an increasing rate of 0.023°C per year. The northern part (north to 5°N) also sustained a boreal summer warming from the 1960s up to the present (not shown), but in an absolute range reduced by half when compared with that of the southern part.

Outside the large positive areas, three small negative areas appear in Figure 9. They were already present in the simple PS − HL field (Figure 2). Two domains are located along the African coast. The first one is adjacent to the northern limit, and the second one is spreading along the coast of Angola. A third negative domain is located close to the mouth of the Amazon River. We searched for some confirmation of these climatic deviations in the literature or from analysis of independent data sets. Oceanic data of SST time series, sufficiently long (i.e., with a beginning before 1940) and

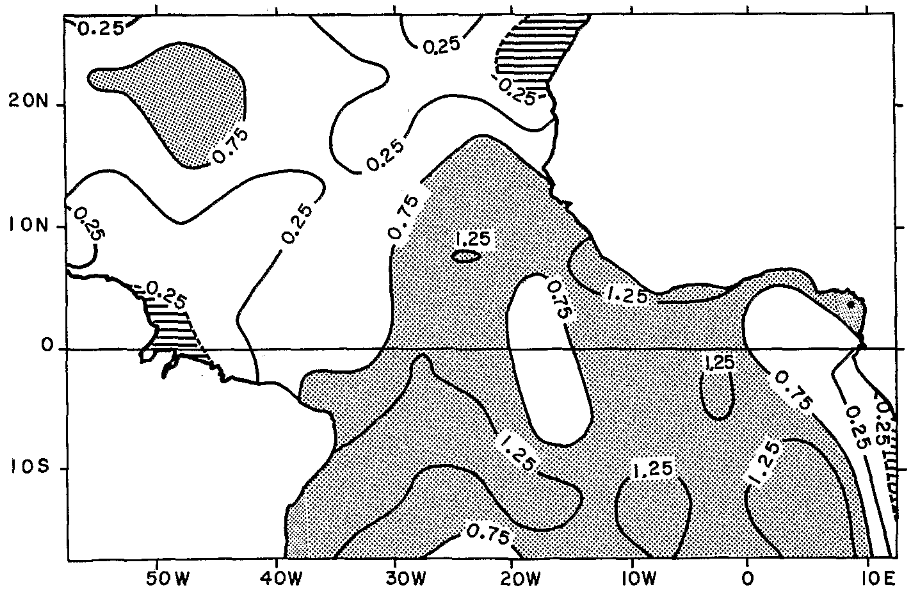

Fig. 9. Spatial pattern of SST trend in degrees per century resulting from the comparison between the PS and the HL climatologies. The stippled areas correspond to a "warming" up to +0.75°C per 100 years. The hatched areas correspond to a "cooling" down to −0.25°C per 100 years. The spatial grid is 5° longitude by 5° latitude.

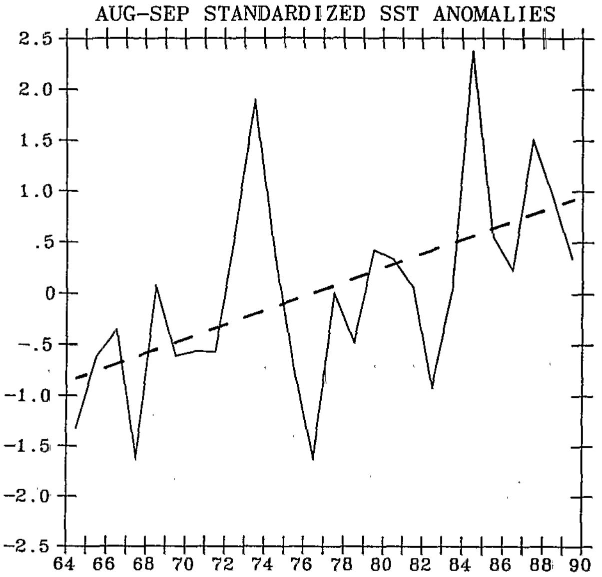

Fig. 10. August–September SST standardized anomalies averaged over the oceanic basin between 5°N and 20°S through the 1964–1989 period. The dashed line represents the linear adjusting function.

derived from nonmerchant ship observations, are sparse. An alternate possibility is to look at the trend of the air temperature when analyzing time series derived from seaside observations.

For the eastern regions located along the African coast, some material supports our observed climatic change. For example, *Le Goff* [1985], when analyzing a 1936–1980 time series of air temperature on the Morocco region, found a 1°C drop during that period. That region is situated along the northern limit of our study area. In addition, the argument for such a climatic change is supported by *van Loon and Williams* [1976], who noted a cooling along the Mauritania-Senegal coast, principally during the summertime. Looking at their Figures 1 and 2, one can note a cooling during the 1942–1972 period (a slope in the linear regression up to −0.06°C per year) stronger than during the 1900–1941 period (a slope of the linear regression close to −0.02°C per year). Moreover, according to Van Loon and Williams' figures, unceasing warming occurred during the entire study period (1900–1972) in the vicinity of the northern limit of the Gulf of Guinea. The slope of the linear regression (close to +0.02°C per year) in that region could induce a total air temperature heating of up to 1°C. This conclusion agrees with our own result shown in Figure 9. *Höflich* [1973] also exhibited a further important warming of SST compared with air temperature during the 1910–1969 period in the equatorial region (see his Figure 14). For the southeastern limit of our area of interest, an available time series of air temperature related to the Angola coast (Y. Gallardo, personal communication, 1986) showed a mean drop of 0.5°C between the 1930–1940s and the 1960–1970s.

Entire air temperature time series which originate quite early in this century are not available for the vicinity of the Amazon River mouth, where we observed a negative difference in the oceanic temperature between PS and HL (Figure 9). However, an air temperature drop of about 0.5° between the 1930s and 1960s at the northern limit of this area is found when analyzing the time series of the meteorological station of Paramaribo (Surinam). South of the equator, the important positive trend observed in SST along the eastern coast of Brazil (see Figure 9 for centennial extrapolated values up to 1.25°C) seems to be in harmony with a difference of 0.6–0.7°C noticed in the air temperature time series related to Salvador between the 1920–1930s and the 1940–1960s.

5. Recent Observations Versus HL and PS Climatologies

Since 1981 (prior to the start of the FOCAL/SEQUAL experiments (1982–1984) and the present TOGA program (1985–1995)), expendable bathythermographs (XBTs) have been regularly launched by ships of opportunity along the Europe-Brazil route between 20°N and 20°S (see the position of this transequatorial line in Figure 1). A time-space diagram of the annual mean surface temperature (measured at 3.5 m deep) derived from this data set is shown in Figure 11*a* from 1981 to 1985. Independent of the years, three main regions can be distinguished: (1) north of 8°N, where a strong meridional thermic gradient occurs; (2) the equatorial region, which is very warm (above 27°C); and (3) the Brazilian water, south of 10°S, which is slightly cooler than the equatorial water. The southern region warmed by 1°C between 1981 and 1984–1985 (+2° to +2.5°C for some monthly means, not shown). The other two regions experienced lower temperature changes, of the order of ±0.5°C.

One prime question is, How different is this 1981–1985 situation from the climatic mean? The answer depends on the reference climatology. First, using the HL climatology as a reference (Figure 11*b*), 1981–1985 temperatures were generally warmer than normal with maximum positive anomalies exceeding 1.2°C at the north and south extremities of the study line. Such values are exceptional for annual SST departures in the tropical Atlantic Ocean. The northern anomalies, mostly above +1°C, can be interpreted as a decrease in the offshore extensions of the Mauritania-Senegal upwellings or a decrease of their intensities. The temperature in the vicinity of the Guinea dome (centered at 10°N and 22°W) [*Voituriez*, 1981] was almost normal throughout the 1981–1985 period, while for the equatorial region the annual anomaly increased from 0.4° to 0.8°C between 1982 and 1984. This cannot be only due to a decrease in the western extension or duration of the seasonal equatorial upwelling (occurring in July–September), as warm season temperatures (occurring about April) also increased by almost +1°C between 1981 and 1984 [*Rual and Jarrige*, 1984]. The Brazilian water temperature was normal in 1981 but increased drastically to reach a +1.2°C anomaly in 1984. Because the thermocline in this area is about 100 m deep, a huge amount of extra heat was stored during 1984 in the ocean along the coast of Brazil.

On the other hand, if the PS climatology is used (Figure 11*c*), the 1981–1985 situation fluctuated around the mean. Only three anomalies, two in the northern region, in 1981 and 1985, and one in the southern one in 1984, are about two standard deviations away from the mean. The rest of the area is within one standard deviation about the mean. Moreover, Figure 11*c* illustrates very well the north-south climate dipole noted in section 4. Until 1983, there was cold SST off the Brazilian coast and warm SST north of the thermal equator. This phenomenon is typical of a drought

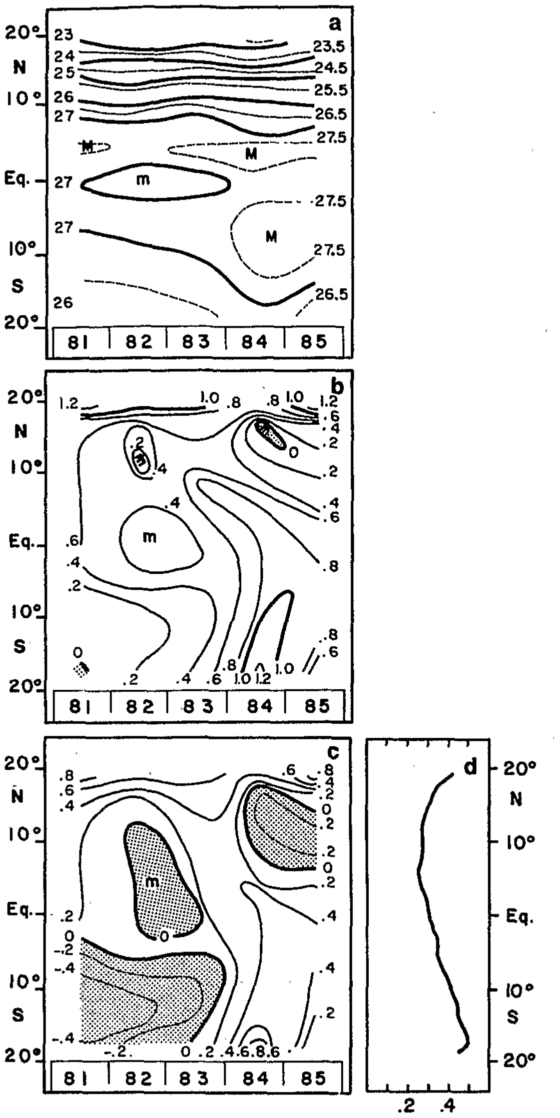

Fig. 11. (*a*) SST (in degrees Celsius) observed along the shipping route Europe–South America between 20°N and 20°S (see Figure 1) during the years 1981–1985. (*b*) SST anomalies (in degrees Celsius) computed when taking the HL climatology as reference. (*c*) SST anomalies (in degrees Celsius) computed when taking the PS climatology as reference. (*d*) Standard deviation of the annual mean temperature anomalies (in degrees Celsius) of the PS climatology taken along the study line. The stippled areas correspond to negative SST anomalies.

situation over northeast Brazil [*Hastenrath and Heller*, 1977; *Moura and Shukla*, 1981; *Servain*, 1985] which was the case. The dipole reversed during 1984–1985, years with excessive precipitation over northeast Brazil.

Another question is, How strong are the 1981–1985 interannual variations compared to previous episodes? In order to illustrate that point, it is advizable to use only the most homogeneous data sets, in this case, the PS data set. Excluding the equatorial wave guide (2°N–2°S), which is subject to specific dynamics, the temperature anomalies of the southern region along the shipping route Europe–South America are coherent enough to be averaged. Figure 12 shows the time series between January 1964 and October 1989 of such a monthly mean anomaly averaged between 2°S and 20°S, using the more recently updated PS data file. This figure shows that the 1981–1982 cold event and the 1984–1985 warm event were not as extreme as the 1964–1989 events. Along the study line off the Brazilian coast, SST was coldest in 1968 (when a strong positive anomaly developed inside the Gulf of Guinea) [*Lamb*, 1978*b*; *Picaut et al.*, 1985] and warmer in 1988 and in 1973 (when the whole basin south of the thermal equator was warm) [*Picaut et al.*, 1985].

6. Concluding Remarks

Simple numerical investigations of discrepancies between two climatologies of SST over the tropical Atlantic Ocean allow examination of large-scale variations during this century. The evidence points to a warming trend in a large area south of the thermal equator. For this region, our study displays increases in the mean annual temperature of up to 0.4–0.6°C between the 1940s and the 1970s. The observed rise appears valid even after biases from observing techniques are subtracted. Nevertheless, off the Angola coast, a spatially limited region with a seasonal upwelling, it seems that the climatic trend was reversed during the same period. We disclose that the large-scale southern warming was primarily due to SST increases occurring during the end of boreal summers. This trend is still going on with an enhanced range: the August–September SST anomalies averaged over the total southern basin increased by 0.6°C during the past 26 years.

North of the thermal equator, the situation is not so clear. Here the large-scale observed temperature rise between the 1940s and the 1970s (less than 0.4°C) can be entirely explained by observing technique bias. In fact, after subtracting the bias, it is possible for the temperature to fall, especially during the boreal summertime. When studying large-scale time series of the northern part through the past 25 years, a warming summer trend is noted but in a range drastically narrower than that of the southern part. Cooling between the 1940s and the 1970s is supported for two spatially limited areas, the first one close to the Mauritania-Senegal upwelling and the second one in the vicinity of the Amazon River mouth.

Our study confirms the tendency for the thermal state of the tropical Atlantic Ocean to settle down through a north-south climatic dipole. Monitoring the fluctuations of this dipole (associated with abnormal latitudinal position of the Intertropical Convergence Zone) is of prime importance because they are linked to variations in precipitation regimes over northeast Brazil or African Sahel [*Servain*, 1985].

Another conclusion which emerges from this study relates to the precautions which must be taken when analyzing the merchant ship observations, either from raw data or from derived product files. Users of such information are advised to keep in mind the spatial and temporal densities of the number of available observations. Moreover, when comparing specific observations to distinct climatologies, conclusions may differ greatly, even if the mean difference between the climatologies of reference seems weak. In consequence, any SST climatology performed from merchant ship observations (and presently this data source is still necessary to produce large-scale climatologies) should be based on data since the 1950s.

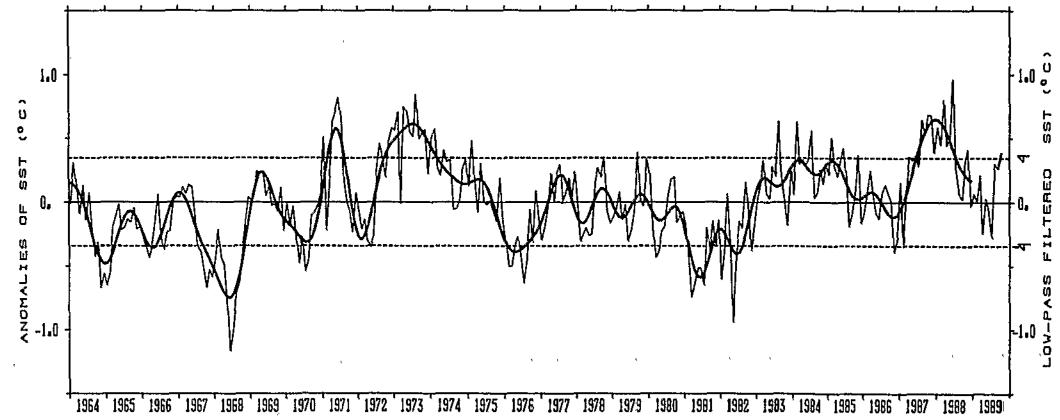

Fig. 12. Monthly mean anomaly of SST (in degrees Celsius) from January 1964 to October 1989 averaged between 2°S and 20°S along the Europe–South America shipping line. The low-frequency curve, up to December 1988, is the result of a low-pass filter (>12 months). The dashed lines indicate the range of the annual standard deviation of the monthly anomalies.

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P. Rual, Centre ORSTOM, BP A5, Nouméa, New Caledonia, West Pacific.

J. Servain, Centre ORSTOM, IFREMER, BP 70, 29280 Plouzané, France.

M. Séva, Université de Bretagne Occidentale, 6 Avenue le Gorgeu, 29200 Brest, France.

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