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ANNUAL SIGNAL AND INTERANNUAL ANOMALIES OF SEA SURFACE TEMPERATURE IN THE EASTERN EQUATORIAL ATLANTIC OCEAN

J. Merle*, M. Feux** and P. Hisard***
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Abstract--Analysis of historical data including coastal and open ocean data provides a quantitative description of the characteristics of the sea surface annual signal and of the interannual anomalies in the eastern equatorial Atlantic Ocean. The annual signal has a larger amplitude than the interannual anomalies but has considerable spatial variations. In two regions, namely the northern coast of the Gulf of Guinea and the equator, both annual and interannual variability are particularly large because of a seasonal surfacing of the thermocline. Eastward advection of warm water by the Countercurrent system, local rain and runoff of great rivers could contribute significantly to the seasonal and interannual SST variability. Interannual anomalies have a large spatial extent and can affect the whole basin for several months or a year. In the Atlantic as in other regions of the world ocean, the long-term trend shows a general increase of SST from the beginning of the century to the sixties and a decrease until now.

INTRODUCTION

Numerical models suggest that the atmospheric circulation is very sensitive to sea surface temperature (SST) in the tropics (Rowntree, 1973; Shukla, 1975). Even at low latitudes the SST has strong spatial and temporal variations. The eastern part of the equatorial regions both in the Pacific and in the Atlantic oceans are relatively cold; the western parts, on the contrary, are generally warmer and almost isothermal year-round. Thus an east-west SST gradient appears. The atmospheric "Walker circulation" is

* CIMAS (Miami) and ORSTOM (Brest-France)

** CNRS - Museum (Paris-France)

+ ORSTOM (Abidjan-Ivory Coast)



maintained by this longitudinal thermal ocean gradient.

In the eastern Pacific Ocean this equatorial cold water is quasi-permanent, but can be affected by strong interannual anomalies, such as those associated with "El Niño" when the surface is covered by a shallow warm layer for several months. In part of the Pacific Ocean the interannual variability of SST is larger than the mean annual signal; see for example the Canton Island station records (Bjerknes, 1969).

In the Atlantic Ocean, on the contrary, the equatorial cold water appears only during the summer season (June-September), thus giving a large amplitude to the annual signal (Merle and Le Floch, 1978). Hence in the Atlantic Ocean the mean annual signal is stronger than the interannual variability. This large annual signal reaching 6 or 8 C at the equator can be well represented by the composition of the two first terms of a Fourier's series of annual and semi-annual periods. The amplitude of the semi-annual periods is relatively large and represents more than half of the amplitude of the annual period (Merle and Le Floch, 1978).

The seasonal variations have their largest amplitude in the upwelling regions: coastal upwelling (Ivory Coast, Ghana, Congo, Angola) or equatorial upwelling (mainly in the area limited by $0-3^{\circ}$ and $0-10^{\circ}$ W). In these areas the increase in amplitude is obviously due to the intense surface summer cooling of July-September. Superimposed on the annual cycle are fluctuations over a spectrum of frequencies. Particularly pronounced are waves with a 14.7-day period (Houghton and Beer, 1976; Picaut and Verstraete, 1979).

Our purpose is to concentrate on a description of the annual signal of the sea surface temperature as it appears in various places of the coast along the Gulf and in the open ocean. We also investigate the interannual anomalies; their magnitude is compared with the annual signal.

DATA AND PROCESSING

We have used three sets of historical data:

1. Marine deck sea surface observation records on file at the National Weather Records Center, Asheville, N.C. are used. Space and time distribution of these data are very heterogeneous and concentrated along ship-lines; there is a lack of data during the two world wars. Our study will mainly use the eastern ship-line crossing the Gulf of Guinea and the equatorial region between 5° W and 10° W where the coldest upwelled water is observed in summer. We shall also consider the meridional strip from 10° N to 5° S around 23.5° W, Marsden square 300 and 371 as a whole and a 1° strip along the Ivory Coast (Fig. 1).

Mean and standard deviations of SST for each month and each degree square have been computed for each year of the period 1920-1970. Only squares where more than 5 observations are available have been considered. Generally along the main ship-line crossing the Gulf of Guinea more than 10 observations are available for each month and each degree square. Standard deviations are large (from 0.5 C to 2 C), but the means are

consistent in space. The magnitude of the annual and interannual variability is discussed in the next section.

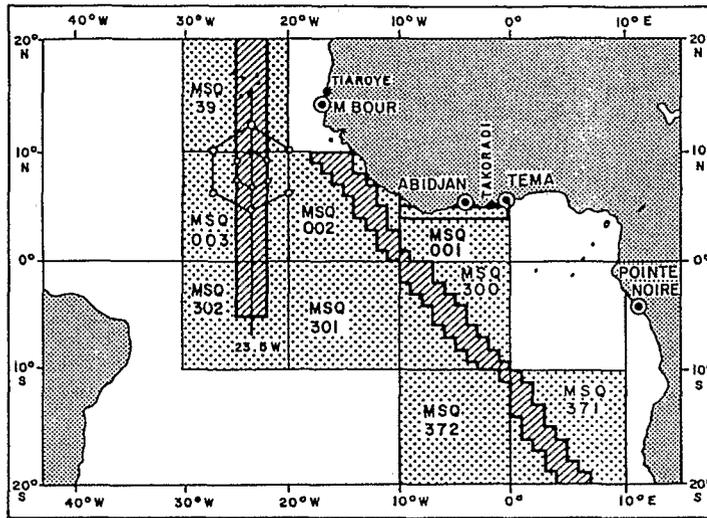


Fig. 1. Distribution of the marine deck data used. For an estimation of the number of the data available in each degree square see Hastenrath and Lamb (1977) Plate 1. Shaded strips are related to Figures 7 and 9.

2. A series of several years of daily coastal observations in different points of the Gulf have been recorded by ORSTOM oceanographers in the Ivory Coast and Congo and by the Fisheries Research Unit of Ghana and some observations made in Angola are also used in this paper. Our study is limited to the sea surface temperature. Positions of the stations are indicated in the lower part of Figure 4.

3. NANSEN data provided by the U.S. NODC in the open ocean are considered through the monthly mean of all years by squares of 4 degrees in longitude and 2 degrees in latitude.

ANNUAL AND INTERANNUAL VARIABILITY

It is commonly asserted that in the eastern tropical Atlantic Ocean the SST annual signal is larger than the interannual variability in contrast to the eastern tropical Pacific Ocean where the interannual anomalies have a dramatic amplitude (El Niño).

The power spectrum of the largest coastal time series provides a first attempt to verify this point. Figure 2 shows that for the main coastal station three large peaks at the annual, semi-annual and four month period are observed, but after subtracting the non-

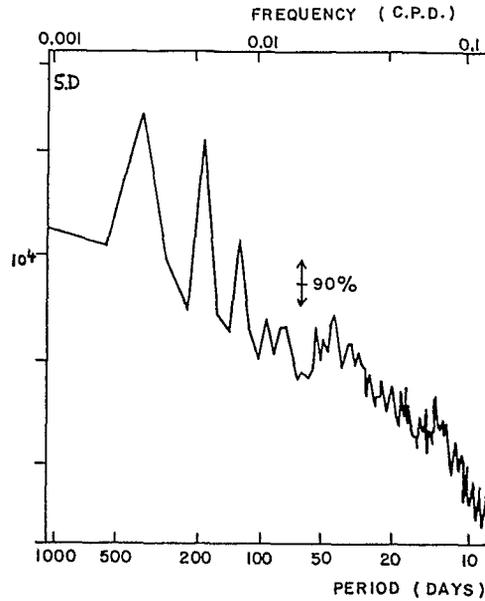


Fig. 2. Spectrum of SST at Tema station for 13 yrs record.

sinusoidal mean annual signal, the spectrum does not show the peaks at these periods (Verstraete, Picaut and Morliere, 1979). We can conclude that the annual signal is the dominant signal in the period range of variability from days to several years.

Analysis of variance both at the coastal stations and along the shipline crossing the Gulf gives the opportunity to confirm this result and to determine the spatial and temporal scales of variability in the SST. We can consider a monthly variability represented by the variance of all the observations made in a given month. This variance includes both the physical variability of the phenomenon of periods less than 1 month and the noise due to the data collecting procedures. We denote this variance by S_M^2 ; its mean for all the months of the time series is $\overline{S_M^2}$. A measure of the annual variability is S_A^2 : the variance of all the mean monthly values of a given year. The mean of S_A^2 for all the years for which data are available is $\overline{S_A^2}$. The difference between February (say) of different years determines interannual variability. Definitions for S_{IA} and $\overline{S_{IA}^2}$ are obvious.

Along the shipline for each of 1 degree of latitude from 20°S to 10°N and for the period 1921-1970 we have calculated S_{IA} for February and August and $\overline{S_A}$. The results are shown in Figure 3a. Note that the annual signal is generally larger than the interannual variability but there are important spatial variations along the shipline.

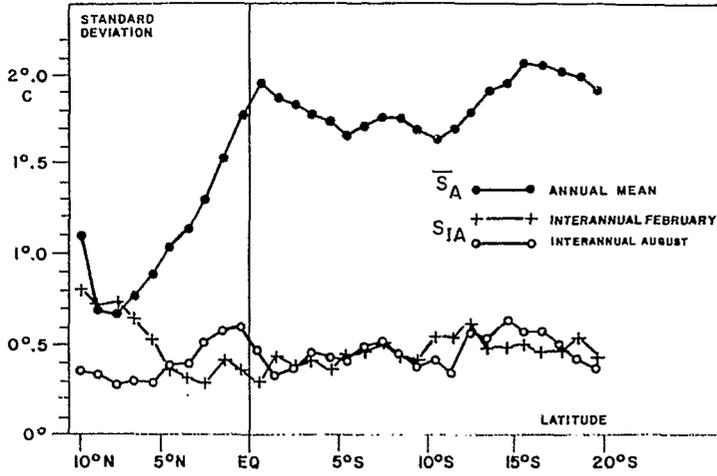


Fig. 3a. Meridional variation along the shipline crossing the Gulf of Guinea, of the standard deviation of the monthly mean value (mean annual variability) and of the interannual anomalies for February and August (interannual variability). In each square of 1 degree of latitude and 3 degrees of longitude along the shipline of the Gulf of Guinea and from 1920 to 1970 we have about 300 to 3000 observations each month. For a more precise repartition of the data see Hastenrath and Lamb (1977) Plate 1.

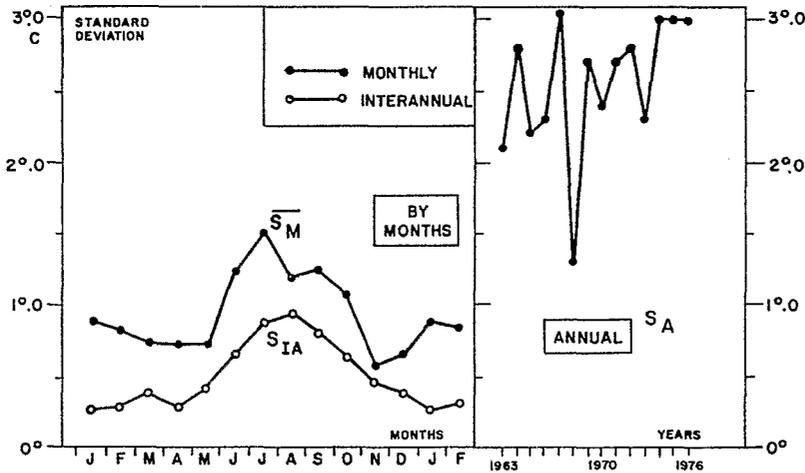


Fig. 3b. Standard deviation of the annual variability from 1963 to 1976 at the Tema coastal station (right). Standard deviation of the monthly and interannual variability for each month of the same period (left).

South of the equator the standard deviation (SD) of the mean annual cycle is between 1.6 and 2 C; it is 4 to 5 times higher than the SD of the interannual anomalies for February and August.

At the Equator ($3^{\circ}\text{S} - 3^{\circ}\text{N}$) a maximum is reached for the SD of the mean annual variability (≈ 2 C); for February the SD of the interannual variability near the equator is small but for August we observe an increase up to 0.6 C at the Equator. North of the equator the SD of the mean annual cycle decreases sharply to 0.7 C at $7-8^{\circ}\text{N}$. SD of the interannual variability in August also decreases from 0.6 C to 0.3 C, but in February, on the contrary, the interannual SD increases rapidly from 0.3 C at 5°N up to 0.8 C at 10°N and reaches the same value as the SD of the mean annual variation near $7-8^{\circ}\text{N}$.

At the Tema coastal station we have calculated S_{IA} , $\overline{S_M}$ and S_A for the period 1963-1976. The results (Fig. 3b) show that at the coastal station the annual variability is higher both than the interannual variability and the monthly variability. SD of the monthly mean value in the annual cycle (annual variability) is between 2 C and 3 C except in 1968. SD of all the observations in a given month (monthly variability) has a mean of 1 C but varies seasonally from 0.7 C in winter to 1.5 C in summer. SD of the interannual anomalies (interannual variability) is lower with a mean of 0.5 C but also has seasonal variations from 0.3 C in winter to 0.8 C in summer.

In conclusion, the coastal and open ocean SST data files demonstrate that the annual signal is much larger than the interannual and monthly variability. The ratio of standard deviation of the annual variability to standard deviation of the interannual variability are found to be nearly equal at the coast and in the open ocean. SD of the annual signal is found to be about five times higher than SD of interannual anomalies and 2.5 times higher than SD of the monthly variability. Nevertheless, important seasonal and spatial variations of these ratios are observed.

ANNUAL SIGNAL

At the Coast (Coastal Data)

Figure 4 shows the mean annual signal of all the coastal stations considered. Table 1 gives the mean characteristics of their annual and semi-annual components in a 2-term Fourier analysis. Amplitudes and phases are relatively stable from one year to another. For all the stations the SD of the phases is between 5 and 15 days and the SD of the amplitude is generally less than 0.5 C. The semi-annual components have a smaller SD than the annual components both for amplitudes and phases. From the south to the north, the mean characteristics of the observed annual signals vary significantly.

South of the equator, Lucira (14°S) and Pointe Noire (4°S) present a large annual and semi-annual amplitude: 3.5 C to 4 C for the annual amplitude and about 2.5 C for the semi-annual amplitude. Phases indicate a cold season arrives here earlier than further

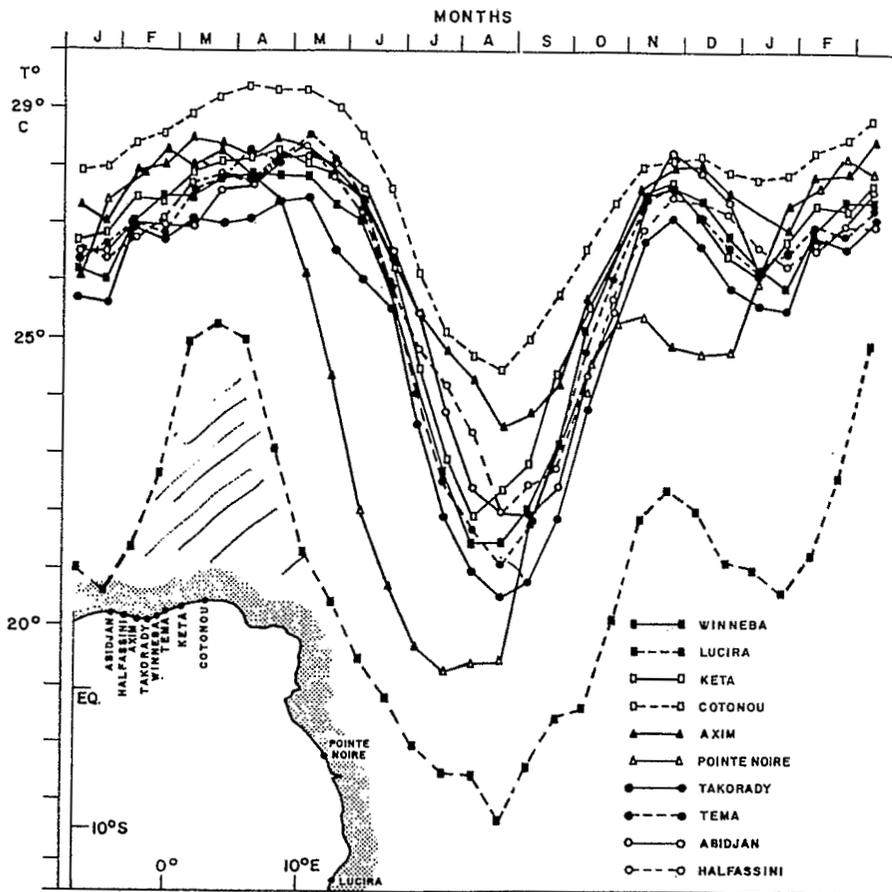


Fig. 4. Mean annual sea surface temperature cycle for various coastal stations in the Gulf of Guinea, averaged by half months. Confidence interval (95%) is less than 0.1 C except for Lucira station.

north. The phase differences between Pointe Noire and Tema are 21 days for the annual phase, 33 days for the semi-annual phase and 27 days for the date of the cold season.

Along the E-W coast from Cotonou to Abidjan, annual signals have the same feature with a relatively short main cold season (three months) and a long warm season of eight months from November to June; however, a secondary slight cold season appears in January so that all the records show a bimodal annual signal. Amplitudes of both the annual and semi-annual components are variable from one station to another; the largest amplitudes are found to the east of the Cape. Four points (Takorady, Winneba, Tema, Keta) have

TABLE 1 Mean amplitudes and phases of annual and semi-annual components at coastal stations. Standard deviations are indicated.

	Abidjan	Halfassini	Axim	Takorady	Winneba	Tema	Keta	Cotonou	Pointe Noire
Annual Amplitude (degrees C)	2.27	2.05	1.90	2.67	2.29	2.44	2.39	1.71	3.89
S.D.	0.66	0.42	0.22	0.43	0.50	0.81	0.30	0.52	0.55
Semi-Annual Amplitude (degrees C)	1.92	1.46	1.10	1.85	1.79	1.91	1.71	1.04	7.79
S.D.	0.33	0.24	0.23	0.79	0.36	0.35	0.17	0.20	0.3
Annual Phase (days)	54.6	56.3	52.0	49.8	46.0	53.9	46.7	59.7	33.3
S.D.	14.4	8.7	7.1	9.7	9.5	8.4	7.9	7.1	11.3
Semi-Annual Phase (days)	137.8	135.3	129.0	130.1	127.1	128.9	124.9	125.9	97.1
S.D.	10.4	5.8	4.6	6.9	5.5	6.5	5.4	5.2	9.4

about 2.5 C for the annual amplitude and 1.8 C for the semi-annual amplitude. West of the cape (Axim, Halfassini, Abidjan) amplitudes are smaller: 2.0 C for annual amplitude and 1.4 C for semi-annual amplitude. These marked differences in relation with the orientation of the coast suggest that the local winds which are parallel to the coast east of the Cape influence the coastal upwelling.

The phases are more stable than the amplitude but significant differences are found in the semi-annual phases and in the date of the cold season, suggesting a westward propagation of the annual signal. This point will be discussed further.

In The Open Ocean (NANSEN Data and Marine Ship Data)

NANSEN data are more homogeneously allotted in space than the marine ship sea surface observations. Using this file, Merle and LeFloch (1978) present the distribution of the annual signal in the whole intertropical Atlantic Ocean ($20^{\circ}\text{N} - 20^{\circ}\text{S}$). Seasonal variations of sea surface temperature are important in the eastern tropical Atlantic Ocean. The amplitude of the annual and semi-annual period have large spatial variations (Fig. 5a and b).

The distribution of the amplitude of the annual period shows a marked maximum reaching 2.5 C in the equatorial area, but the largest values are found near the East African coast south of the equator. Along the E-W coast another area of relatively important annual amplitude (2.2 C) is associated with the coastal upwelling. A minimum (less than 0.5) crosses the Atlantic from 3°N near the Brazilian coast to 8°N near the African coast; it is the north-south thermal transition zone. The amplitude of the semi-annual component increases in the eastern Atlantic Ocean, but rarely reaches 1 C; a maximum is also found in the equatorial divergence area and along the E-W coast.

Phases are not as consistent as amplitude and we have only mapped it in the Gulf of Guinea where the number of observations is larger. The phases of the annual component (Fig. 6a) increase along the equator from the east to the west until 10°W suggesting also in the open ocean a propagation of the seasonal signal toward the west. Near the E-W coast, on the contrary, no clear variation and propagation of the annual phase appears. Phases of the semi-annual component (Fig. 6b) reach a maximum of about 140-160 days (end of April - beginning of May) in a large zone between 1°N and the E-W coast (5°N); it seems also that the region of the north-south transition near $6-8^{\circ}\text{N}$ and west of 12°W , where a minimum of the annual amplitude is observed, is characterized by a late date in the semi-annual phase (more than 150 days).

Using the marine ship data we shall consider two regions (Fig. 1).

a) A meridional band of 3° wide around 23.5°W from 5°S to 15°N crossing the center of the B/C scale GATE area.

b) The ship line from 10°N to 20°S crossing the Gulf of Guinea and the equatorial region at about 10°W .

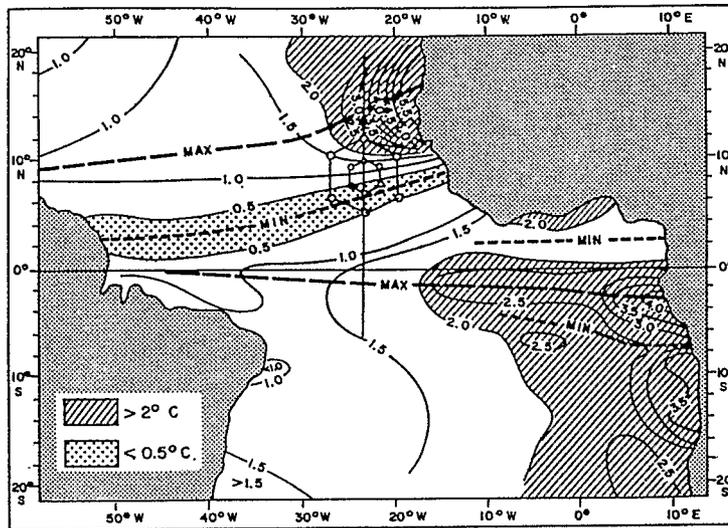


Fig. 5a. Amplitude in degrees C of the annual period in a two-term Fourier analysis of SST using historical Nansen data averaged by month in boxes of 4° longitude and 2° latitude (from Merle and Le Floch, 1978).

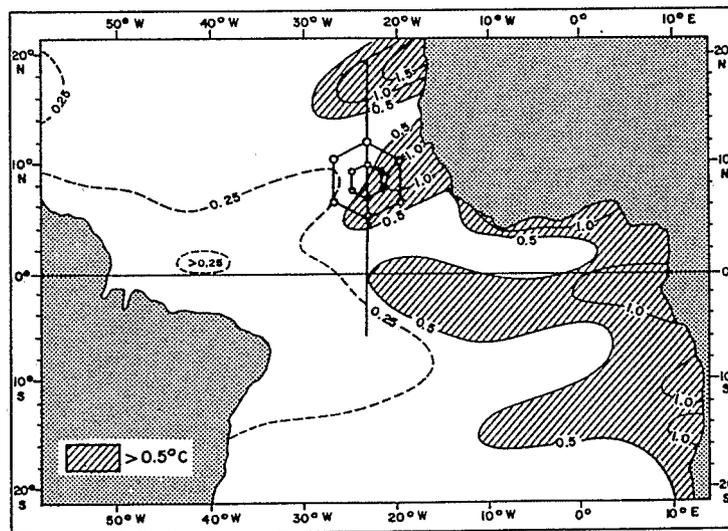


Fig. 5b. Amplitude in degrees C of the semi-annual period.

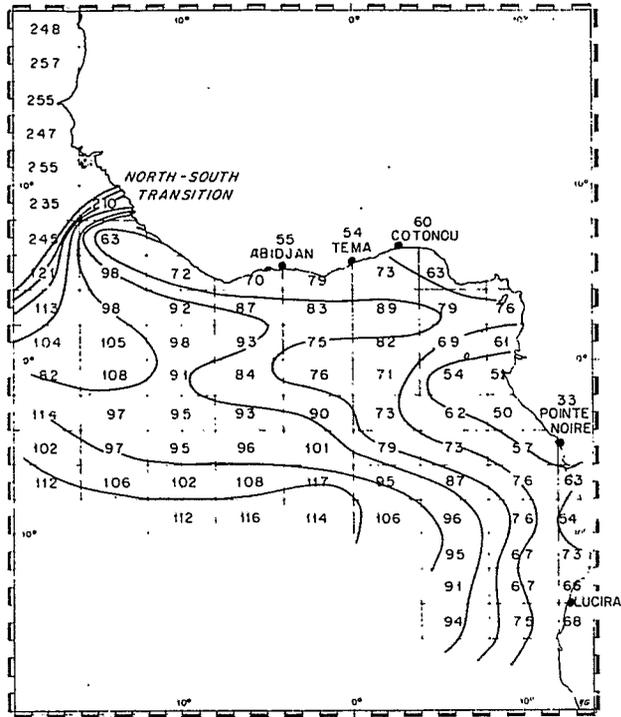


Fig. 6a. Distribution of the phase in days of the annual component in the Gulf of Guinea. Same specifications as Figure 5.

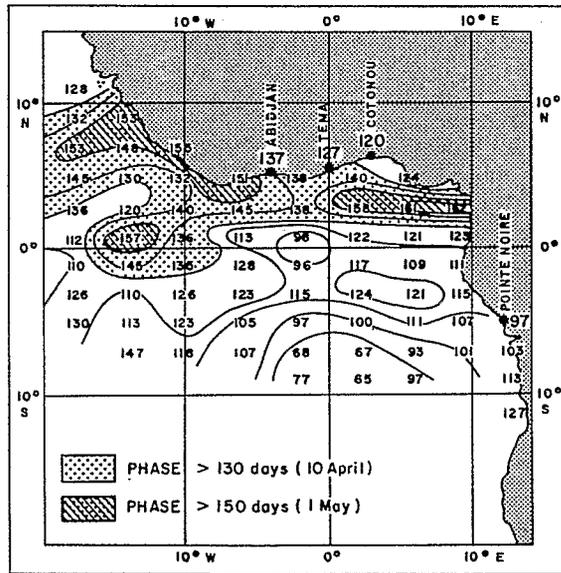


Fig. 6b. Distribution of the phase in days of the semi-annual component in the Gulf of Guinea. Same specifications as Figure 5.

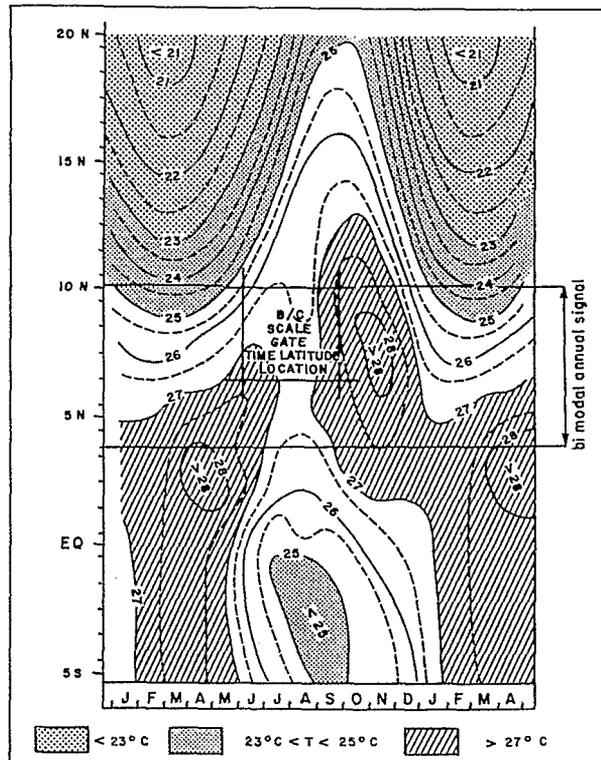


Fig. 7. Time-latitude SST diagram along a meridional band of 3° wide around 23.5°W . Average for each month and each $3^{\circ}\times 1^{\circ}$ box of the 1920-1970 marine deck data. The B/C scale GATE time-latitude location is situated in a double transition zone; space transition between north and south influences; time transition between a southern summer and a northern summer.

Around 23.5°W the time-latitude SST diagram (Fig. 7) describes mainly the north-south transition area. The B/C scale GATE area is located in a region where the SST annual signal is minimum (Fig. 5) under the northern position of the ITCZ (inter-tropical convergence zone) and where absolute values of SST are maximum. This region is also characterized by a bimodal annual signal. Two warm seasons are concentrated in June and November and two relatively cold seasons are concentrated in August and February; thus the GATE period (June-September) in the B/C scale area is situated between the southern summer and the northern summer in a relative cold season corresponding to the southern winter (Fig. 8). Bakun (1978), using the same data set along the African coast, also found a bimodal annual signal to the west of 10°W .

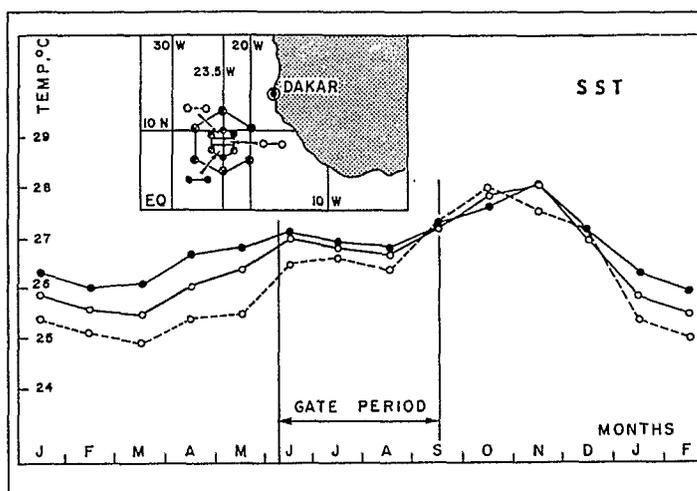


Fig. 8. SST annual signal in the B/C scale GATE area according to the monthly mean 1920-1970 from the marine deck data file.

Along the ship-line crossing the Gulf of Guinea from 20°S to 10°N the time-latitude diagram of SST mainly describes a southern annual signal except beyond 7°N where the bimodal transition zone reaches (Fig. 9). Note that an increase of the summer cooling appears in August between 3°S and the equator. This cooling arrives before the southern winter further south (October) and confirms that the equatorial cold waters are not only due to marine advection by the South Equatorial Current, but that specific equatorial mechanisms induced by remote or local atmospheric forcing are involved in this equatorial cooling (O'Brien, Adamec and Moore, 1978; Philander, 1979).

INTERANNUAL ANOMALIES

Some Characteristics

In order to have a look at the spatial and temporal consistency of the monthly anomalies in the Gulf of Guinea we have compared five sets of data from 20°S to 5°N including a coastal station (Tema) (Fig. 10). The consistency of the SST anomalies seems remarkable; from Tema station to Marsden Square 371 we can see in 1963 very large positive anomalies; 1964 is mainly affected by negative anomalies; 1964-1965 are affected by positive anomalies; 1967 by negative anomalies, and 1968 by positive anomalies. These anomalies have a large extension in the open ocean, at the scale of the basin at least; and

for example, the 1968 summer positive anomaly of July affects the most important part of the Gulf of Guinea (Fig. 11).

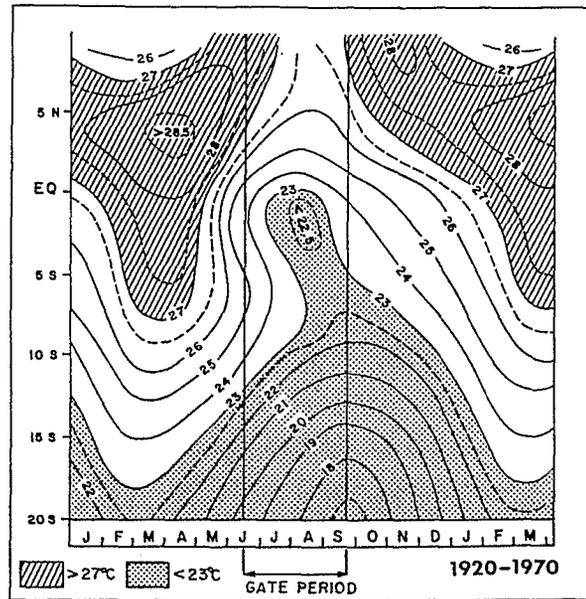


Fig. 9. Time-latitude SST diagram along the ship track line crossing the Gulf of Guinea (see Figure 1). Average of the marine deck data for each month of the 1920-1970 period and where more than 20 observations were available for each degree. Confidence interval (95%) less than 0.1 C.

Looking more precisely at the 1967-1968 oscillation as an example and using a time-latitude diagram along the ship-line crossing the Gulf of Guinea (Fig. 12), we can see that the anomalies, negative or positive, are intensified both at the equator and at the coast (near 10°N) during the summer season. The increase of the SD of the interannual variability in August at the equator has been already pointed out. This intensification of the anomalies is related to the surfacing of the thermocline. This point will be discussed further. The anomalies seem also to appear earlier in the south, suggesting a northward "propagation." The cold anomaly for example appears in March 1967 at 20°S, and is maintained until June 1968 at 10°N, while further south the warm anomaly was appearing.

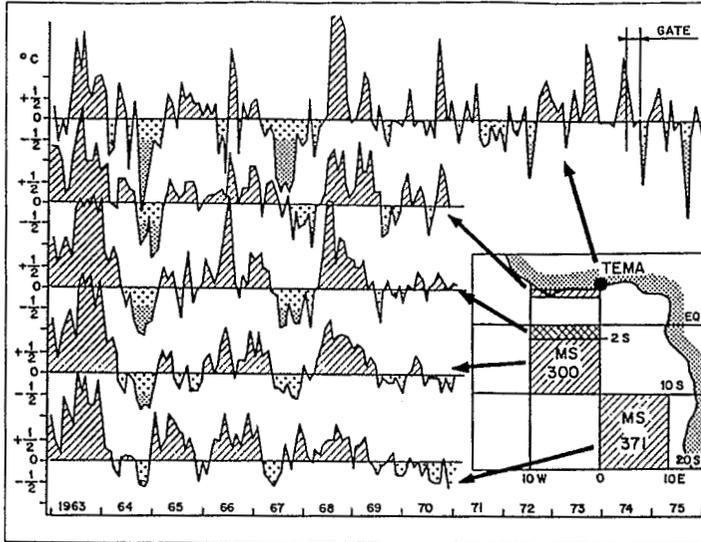


Fig. 10. Time series of SST anomalies from 1963 to 1970 for five sets of data, including Tema coastal record until 1975. The four sets of marine deck data are: latitudinal strip of 10° longitude ($0-10^\circ\text{W}$) between 4° and 5°N along the E-W African coast. An equatorial band 2° wide (Equation -2°S) between 0° and 10°W . The entire Marsden square 300 ($0-10^\circ\text{W}-0-10^\circ\text{S}$). The entire Marsden square 371 ($0-10^\circ\text{E}-10\text{S}-20^\circ\text{S}$). The choice of these areas has been mainly determined by the density and the quality of the data.

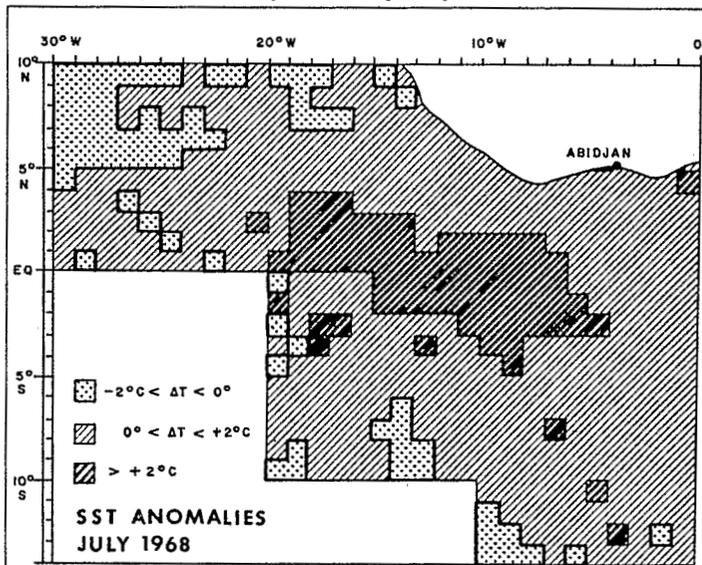


Fig. 11. SST anomalies in July, 1968 in the western part of the Gulf of Guinea. A large positive anomaly of more than 2 C is occupying the main part of the equatorial region. Some boxes without data but surrounded by the same category of anomaly have been interpolated in the picture.

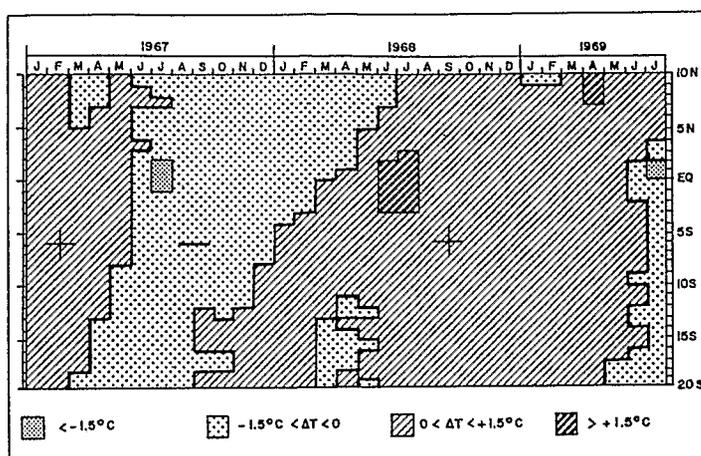


Fig. 12. Time-latitude anomalies diagram along the ship line crossing the Gulf of Guinea for the 1967-1968 oscillation. Anomalies are relative to the mean 1920-1970.

Long Term Trend

In the Marsden Square 300 ($0-10^\circ\text{S}$, $0-10^\circ\text{W}$) and from 1920 to 1970, the monthly anomalies have been plotted (Fig. 13). According to this 1920-1970 mean, we can see a first cold period in 1922-1923 and an intense and long cold period from 1927 to 1933; afterwards warm and cold periods alternate with a quasi-biannual oscillation.

An average over 5 years has been made. A long-term trend seems to exist, showing an increase of SST from the beginning of the century to the period 1960-1965. This trend is also found by Fieux and Stommel (1975 and 1976) in the North Atlantic Ocean and in the Arabian Sea. The comparison is remarkable (Fig. 14). The general warming trend until the sixties and cooling-off thereafter seems to be a world-wide event.

DISCUSSION

We will discuss three points: relation of the annual and interannual SST variability with the subsurface thermal structure; propagation of the annual signal; origin of the semi-annual component of the annual signal.

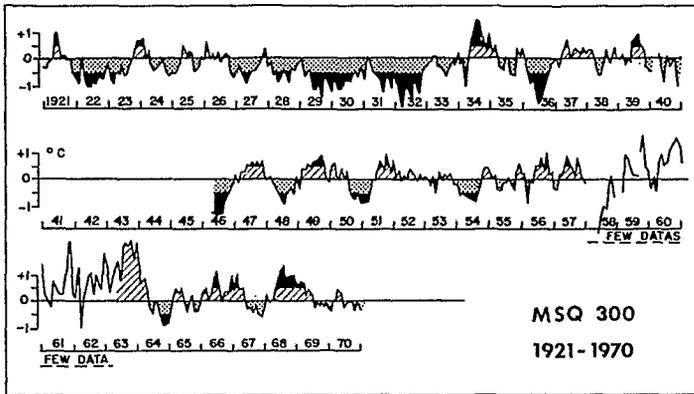


Fig. 13. Monthly anomalies from 1921 to 1970 for the whole Marsden square 300 ($0-10^{\circ}W-0-10^{\circ}S$). No data from 1941 to 1945 and only few data from 1959 to 1962.

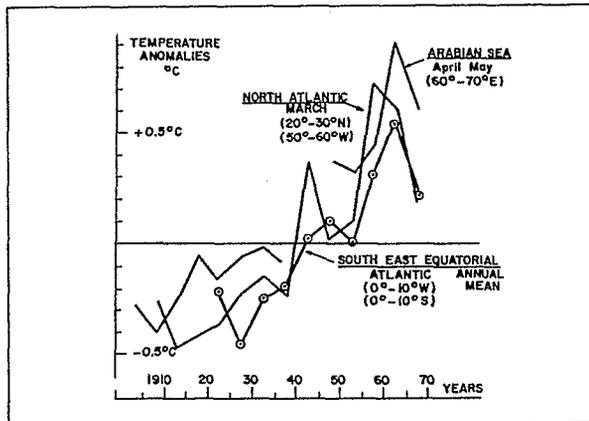


Fig. 14. Trend of the SST anomalies averaged by 5-yr periods in the Arabian Sea, in the North Atlantic Ocean and in the southeast equatorial Atlantic Ocean (MSQ 300). Note the curves representative of the anomalies of the Arabian Sea and the North Atlantic Ocean are relative to a mean for the period 1900-1970. For the southeast equatorial Atlantic Ocean anomalies are relative to the period 1920-1970.

Relation of Annual Signal and Interannual Variability With Subsurface Thermal Structure

The annual signal and the interannual anomalies are intensified in the upwelling areas and in summer. The mean annual depth of the 24 C isotherm, obtained from NANSEN historical data (Fig. 15a), roughly represents the depth of the mixed layer (Fig. 15b) and corresponds quite remarkably with the annual amplitude of the annual signal (Fig. 5a). The seasonal variation of the depth of the 24 C isotherm (Fig. 15c) also indicates a surfacing of the thermocline in summer. Hisard and Merle (1979) show that the equatorial upwelling in June-September near 10°W is due to the surfacing of the thermocline accompanying the core of the eastward Equatorial Undercurrent; the north coastal upwelling in the same season is also associated with the shallowing of the thermocline accompanying the surfacing of the Guinea Counter-current. Thus, the annual and interannual SST variability is directly related to the extension and thickness of the warm superficial mixed layer which create the long warm season by covering during eight months (November-June) the subsuperficial saline and cold water of the thermocline. This superficial curtain of warm water can be considered, by comparison with the eastern equatorial Pacific, as an almost permanent "El Niño" maintained by the North Equatorial Counter Current advection, local rains and runoff of great rivers (Hisard and Merle, 1979). When the rains vanish and after these warm and fresh superficial waters have flowed toward the west (June-July), the normal condition of the eastern equatorial region can appear. The thermocline reaches the surface creating the cold season. If the budget of this superficial warm and relatively fresh water is in surplus, the thermocline remains covered year round. The upwelling season does not appear; the annual signal this year remains almost flat and a strong positive interannual anomaly is observed like in 1963 and 1968.

Propagation of the Annual Signal

The observations in the open ocean (NANSEN data) demonstrate that the annual signal seems to propagate toward the west (Fig. 6a). Along the E-W coast a westward propagation is also observed through the coastal records. A systematic delay of about 10 days in the date of the main cold season between the easternmost station (Cotonou) and the westernmost (Abidjan) is observed (Fig. 16) giving an apparent mean speed of propagation of 80 cm s^{-1} . The phase of the semi-annual component is also affected by a more pronounced westward propagation (Fig. 17). But the phase of the annual component does not show a clear propagation (Fig. 18). Thus, along the coast the westward propagation of the annual signal seems mainly due to its semi-annual component.

Along the E-W coast the relative stability of the semi-annual phase suggests the predominance of an advective phenomenon; on the contrary, the important noise observed in the annual phase could be due to a wave guide effect of the coast. In the open ocean and particularly in the equatorial region, the westward propagation of the annual signal

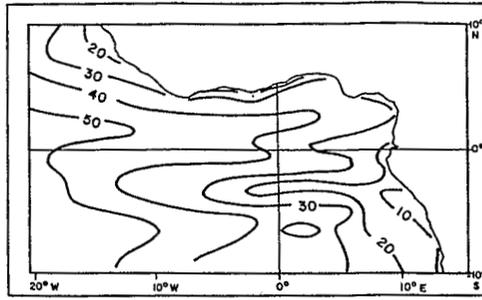


Fig. 15a. Mean annual distribution of the 24°C isotherm in the Gulf of Guinea using historical Nansen data.

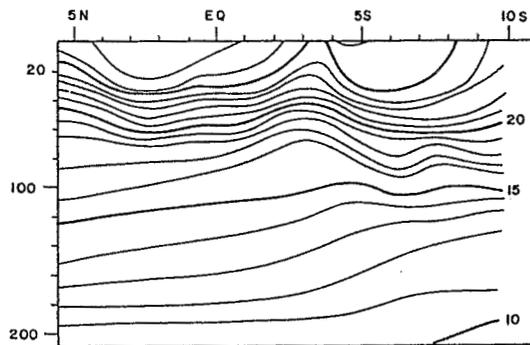


Fig. 15b. Mean meridional annual temperature section from African coast to 10°S and between 0 and 4°W.

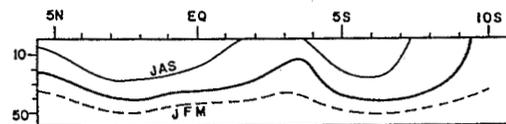


Fig. 15c. Depth of the 24°C isotherm in winter and summer for area defined in Figure 15b.

seems to contradict the hypothesis of an eastward equatorial trapped Kelvin wave involved in the summer equatorial cooling (Adamec and O'Brien, 1978; Moore *et al.*, 1978); but the westward propagation of the annual signal can be interpreted as an interference between Rossby waves propagating westward after reflection on the N-S coast and the eastward Kelvin equatorial trapped wave. Nevertheless it is questionable that the propagation of the

annual signal can be only interpreted in terms of waves; marine advection by the surface and subsurface current system has to be also considered.

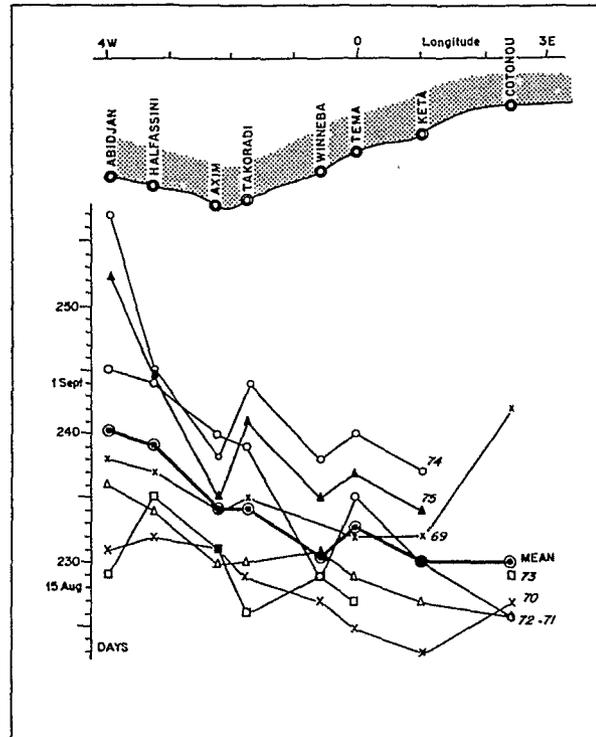


Fig. 16. Date of the main cold season versus longitude for the coastal station of the E-W coast. This date has been computed for several years from the four coefficients resulting of the two-term Fourier analysis.

Origin of the Large Semi-annual Component of the Annual Signal

The two principal factors that influence the SST are radiation and dynamics both of ocean and atmosphere. Between the tropics the sun is at the zenith twice a year at 6-month intervals. So there exists a semi-annual cycle of radiation received at the top of the atmosphere, but this radiation is independent of longitude. The semi-annual component observed in SST is strongly dependent on longitude (Fig. 5b), and so local heating alone cannot explain the observations. Verstraete *et al.* (1979) found a large semi-annual component in wind and pressure at Abidjan and Saint Helena Island ($14^{\circ}\text{S} - 6^{\circ}\text{W}$). The ITCZ crosses twice a year the regions between the equator and $8-10^{\circ}\text{N}$ accompanied by cloudiness and rain. So the semi-annual component of SST could be induced by the local atmospheric dynamics. However, two considerations lead us to also include oceanic dynamics in our explanation. (1) In the eastern equatorial Atlantic, atmospheric forcing is

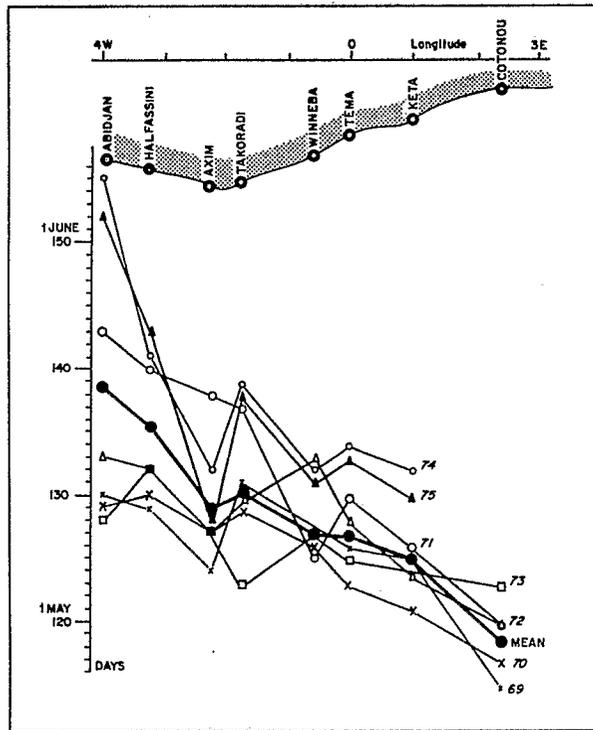


Fig. 17. Phase of semi-annual component versus longitude for the coastal stations of the E-W coast.

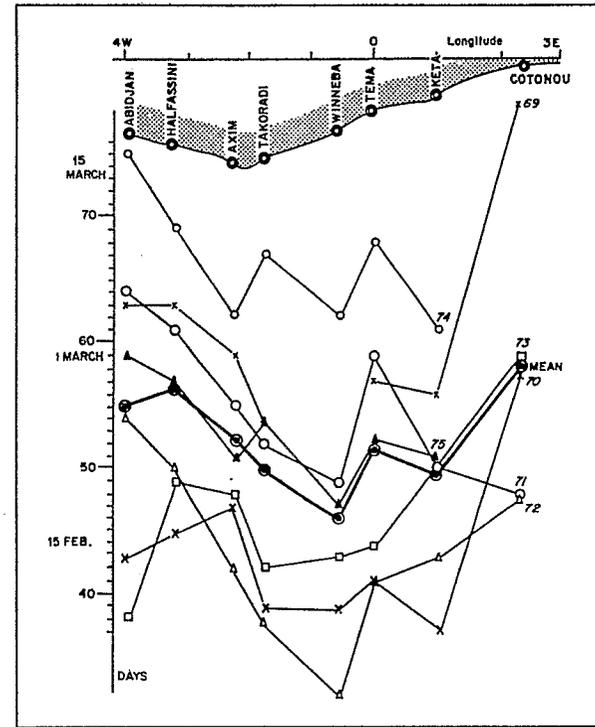


Fig. 18. Phase of annual component versus longitude for the coastal stations of the E-W coast.

weak and even with a marked semi-annual component the annual signal has a small amplitude in wind and pressure. (2) In the subsurface ocean between 20 and 100 m the semi-annual component of the temperature is larger than in surface (Fig. 19); at 50 m and north of the equator the amplitude of the semi-annual component is even larger than the amplitude of the annual component (Merle and LeFloch, 1978). Thus subsurface ocean dynamics could be heavily involved in the observed semi-annual periodicity in SST. A tentative explanation has been proposed involving an alternative advection through the countercurrent system (Merle, 1977). The three Countercurrents, South Equatorial Countercurrent (SECC), North Equatorial Countercurrent (NECC), and the Equatorial Undercurrent (EUC) seem to have strong seasonal variations and to be intensively active during the summer of their hemisphere (the Equatorial Undercurrent is under the main influence of the southern hemisphere and most active from February to April, but it has a secondary active period in fall probably due to a northern hemisphere influence, Neumann *et al.*, 1975). These Countercurrents carry warm water especially during their summer active period. Thus coming alternatively from the northern and the southern hemispheres, for six months, an impulse of warm water flows toward the east, giving by addition of two non-sinusoidal signals a semi-annual signal. The Guinea Current has a first period of eastward warm advection in June-July (Hisard and Merle, 1979) but a second warm advection is also found in October-November; this second warm peak could be due to the NECC discharge two months after its intense summer flow further west in the central Atlantic. On the other hand, the Equatorial Undercurrent, which is the most active in spring, could be responsible for the subsurface warm peak of May-June in the Gulf. It should be noted that if the EUC seems to carry cold water relative to the surface water, it carries relatively warm water in the subsurface due to the equatorial spreading of the thermocline upward and the downward spreading of its core.

SUMMARY

In the eastern equatorial Atlantic Ocean the annual signal is larger than the interannual anomalies but its characteristics have important spatial variations. Two regions are specially affected by large amplitudes in both the annual signal and the interannual anomalies: south of the equator (from 0 to 4°S) and along the E-W coast of the Guinea Gulf. In these areas the thermocline shallows and even surfaces in summer (June-September) suddenly lowering the SST. During the other months (October-May) a thin low saline and warm mixed layer covers the whole Gulf of Guinea giving a long warm season only cut by a slight secondary cold season in December-January. This warm superficial layer calls to our mind a kind of El Niño phenomenon. This warm season could be due to an eastward warm advection and its local consequences: rains and run-off of great rivers. This advection could be complex involving the three branches of the Countercurrent system in an alternative northern and southern influence explaining the strong semi-annual

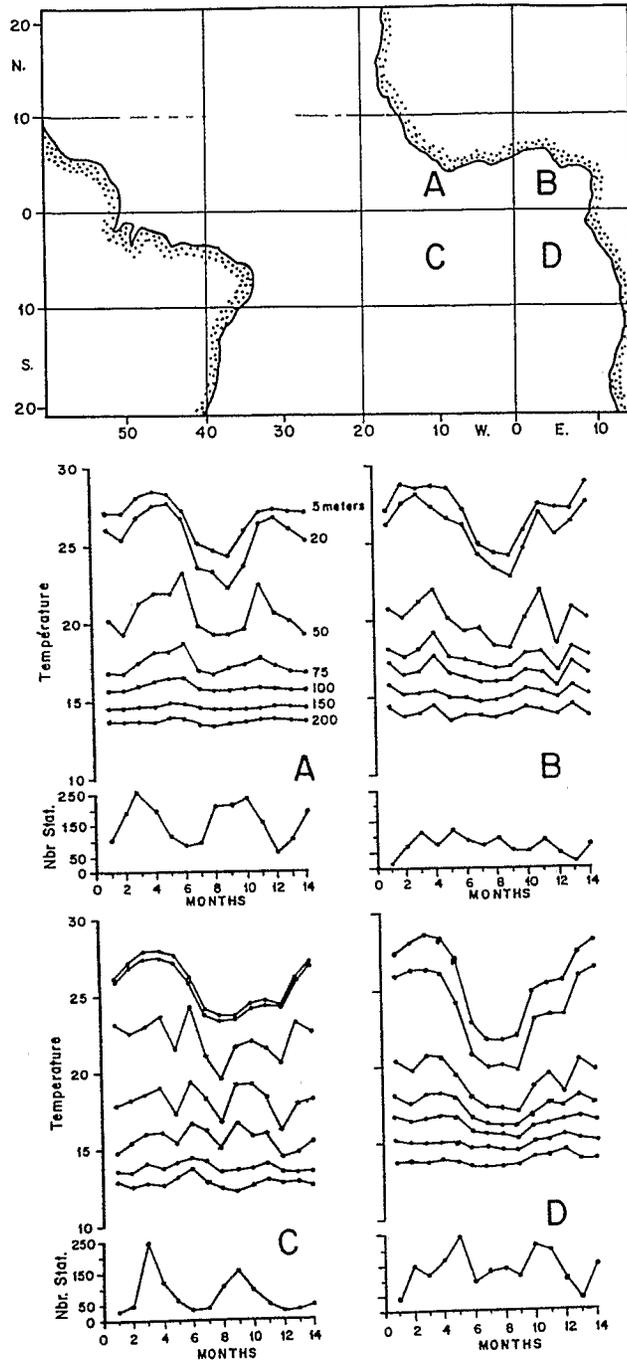


Fig. 19. Annual signal of temperature from 0 to 200 m in four regions of the Gulf of Guinea obtained from NANSEN data.

component responsible for the bimodal temperature annual cycle. The presence of this warm, low salinity surface layer appears to be the leading factor of the SST variability in the annual and interannual time scale whatever the dynamic processes controlling its motion and the motion of the subsurface layers. The westward propagation found for the annual signal could reflect the general westward movement of this superficial mixed layer but could also be related to the equatorial trapped waves (Kelvin) and planetary waves (Rossby) affecting this region.

Interannual anomalies have a large spatial extension at the scale of the basin and affect the region for several months and sometimes more than a year. The magnitude of these anomalies is intensified both at the equator and near the coast. A long-term trend shows an increase of SST from the beginning of the century to the sixties and a decrease until now. This trend is similar to the one observed both in the North Atlantic Ocean and in the Arabian Sea.

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