On the dynamics of thermal variations in the Gulf of Guinea

(with time scales from semi-diurnal to interannual)

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ABSTRACT

This review of dynamic mechanisms associated with thermal variations in the Gulf of Guinea is principally based on our work during the last ten years. In the general introduction we summarize the main features that fundamentally differentiate the low-latitude oceans from the higher ones. The climatic and economic consequences of thermal variations in the tropical oceans are also summarized. The frequency domain of our study is divided into two bands. The first one, defined as medium frequency, focuses mainly on shelf waves (PICAUT *and* VERSTRAETE, *1976, 1979) forced by tides (semi-diurnal and fortnightly) and the atmosphere (period of 40-50 days). In the same frequency range the works of others on Equatorial Undercurrent meanders and oceanic waves are also summarized. For the second frequency band, at seasonal and interannual time scales, our review is mostly concentrated on the remote forcing mechanism of* MOORE et al. *(1978). The main elements of this simple theory are corroborated by analyses of direct and historical observations, i.e. correlation between sea surface temperature in the Gulf of Guinea and zonal wind stress in the western equatorial Atlantic* (SERVAIN et al., *1982), and poleward and vertical propagation of the coastal upwelling in the Gulf of Guinea* (PICAUT, *1983). This remote forcing mechanism is finally detailed by the use of two numerical models.* BUSALACCHI *and* PICAUT *(1983) forced a single baroclinic mode model with realistic coastline and seasonal winds.* MCCREARY et al. *(1984) forced a three-dimensional linear model with simplified coastline and annual winds. These studies, resulting from a close collaboration between theoreticians and observationalists, have enabled a better understanding of the dynamical processes of the variability in the Gulf of Guinea.*

KEY WORDS : Gulf of Guinea — Shelf waves — Equatorial waves — Upwelling — Observations and models.

RÉSUMÉ

SUR LA DYNAMIQUE DES VARIATIONS THERMIQUES DANS LE GOLFE DE GUINÉE
(du semi-diurne à l'interannuel)

Cette revue des mécanismes dynamiques associés aux variations thermiques dans le Golfe de Guinée est basée principalement sur nos travaux depuis une dizaine d'années. Dans l'introduction générale, on résume les traits principaux qui différencient fondamentalement les océans des basses latitudes de ceux des plus hautes latitudes. Les conséquences climatiques et économiques des variations thermiques dans les océans tropicaux sont aussi résumées. Le domaine de fréquence de notre étude est divisé en deux bandes. La première, définie comme de la moyenne fréquence, concerne essentiellement les ondes de plateau (PICAUT *et* VERSTRAETE, *1976, 1979) forcées par la marée (semi-diurne et semi-mensuelle) et l'atmosphère (40-50 jours de période). Dans la même bande de fréquence les travaux d'autres chercheurs sur les méandres du Sous Courant Équatorial et les ondes océaniques sont aussi résumés. Dans la seconde bande de fréquence, saisonnière et interannuelle, notre revue porte essentiellement sur le mécanisme d'action éloigné du vent de* MOORE et al. *(1978). Les principaux éléments de cette théorie sont vérifiés par des analyses de données*

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récentes et historiques, à savoir, corrélation entre la température de surface dans le Golfe de Guinée et tension zonale du vent dans la partie ouest de l'Atlantique Équatorial (SERVAIN et al., *1982*), *et propagations horizontale et verticale du signal côtier d'upwelling dans le Golfe de Guinée* (PICAUT, *1983*). *Ce mécanisme d'action éloigné du vent est finalement détaillé grâce à deux modèles.* BUSALACCHI *et* PICAUT *(1983) ont forcé un modèle à un mode barocline avec une côte et un vent saisonnier réalistes.* MCCREARY et al. *(1984) ont forcé un modèle linéaire à trois dimensions avec des côtes et un vent annuel simplifiés. Ces études, résultantes d'une étroite collaboration entre théoriciens et observateurs, ont permis une meilleure compréhension des processus dynamiques de la variabilité dans le Golfe de Guinée.*

MOTS-CLÉS : Golfe de Guinée — Ondes de plateau — Ondes équatoriales — Upwelling — Observations et modèles.

1. GENERAL INTRODUCTION ON VARIABILITY

1.1. A brief history of the study of thermal variability

HISARD (1983) gives a good historical account of oceanography in the Gulf of Guinea. We notice with HISARD that as early as 1886 a seasonal variation of the hydrographic structure was observed at the equator. And as early as 1906, thanks to the establishment of the first coastal station at Lome (JANKE, 1920), the sea surface temperature (SST) was observed to vary surprisingly within a few days. But for a long time all these variabilities were ignored; the main concern at this time was finding an adequate description of the whole oceans, which were supposed to be stationary. At most, these variations were considered as background noise, interfering with oceanographical measurements. With the discovery, at the turn of the century, of high-frequency internal-wave phenomena, the origin of the interference was ascribed both to internal gravity-waves, with periods ranging from a few minutes to a few hours, and to internal semi-diurnal tidal waves. This concept was reproduced in the first medium and large scale models, which were also stationary, e.g. STOMMEL's (1960) model which extended the classical Ekman theory to equatorial areas.

Curiously, the huge intermediary variability that interests us was uncovered by theoreticians, because ROSSBY (1939), with the ß-plane, introduced the mathematical concept of planetary waves, also known as Rossby waves. In the equatorial strip, meteorologists had to point out the singularities in the Laplace tidal-equations before the idea of equatorially trapped waves became creditable (MATSUNO, 1966). The existence of meridional boundaries hindered the extension of the theories of the equatorial atmosphere to the ocean. MOORE (1968), whose doctorate thesis is still the basis for equatorial theoreticians, has enumerated the corresponding solutions. A great step in the study of an equatorial ocean's response to a variable wind was made by LIGHTHILL (1969), who projected the wind's force on vertical modes. This mathematical approach of summing up the free and forced waves that could be generated left many observationalist oceanographers skeptical as these theoretical results were made with no wave evidence *in situ* at that time.

The main reason for the advance in theory was technical. Until about twenty years ago, oceanographical measurements were taken from isolated ships with methods, such as the Nansen bottle and Ekman current meter, unchanged since the beginning of the century. EQUALANT, between 1963 and 1965, is the first example of a multinational experiment in the tropical Atlantic Ocean. But due to the absence of previous data, this international experiment came up only with the broad pattern of general flow. Thanks to the development of electronic instruments and the increased number of research ships, the access to knowledge of time-dependent phenomena became rapidly easier. This was the main goal in the oceanographic part of the GATE experiment in 1974. Before, there had been some isolated efforts to point out this variability in the tropical Atlantic Ocean. For example, in 1968 and 1972, three times in less than a month, two small areas in the Gulf of Guinea showed a surprisingly large variability in space and time (LE FLOCH, 1970, 1972). But the first proof of equatorial waves in the equatorial Atlantic were obtained by DUING *et al.* (1975) for the surface layers and by WEISBERG *et al.* (1979) for the deeper layers. For the sake of history, we must also remember the analyses of mean sea level by WUNSCH and GILL (1976) in the equatorial Pacific, and the discovery of deep, low frequency equatorial jets by LUYTEN and SWALLOW (1976) in the Indian Ocean. All these discoveries in equatorial areas are parallel to those of meso-scale vortices in mid-latitude oceans, and it seems, therefore, that an enormous amount of energy is stocked up in the ocean, in a time scale ranging from a few days to a few years. The notion, now acknowledged in meteorology, that some of these fluctuations may be at the origin of mean movement is now being debated in oceanography.

The study of tropical variability could be done, as it is in higher latitudes, using a statistical set of numerous systematic measurements that would lead to a semi-empirical model. But, as we shall see, in lower latitudes the mechanisms of this variability are far easier to identify than in mid-latitude oceans. Because of fantastic breakthroughs in computer technology, one would think that a numerical approach should restrict itself to elaborating a sophisticated model duplicating this variability. But, if we were truly to duplicate the ocean, we would have to integrate unsure physical parameters. Therefore, we might find ourselves with a model whose solutions would be as complex as the ocean itself, and furthermore strongly dependent on undefined exchange coefficients, receptacles of our ignorance. The tendency nowadays is towards simple models that enable us to understand the mechanisms of this variability. These models should also be the guide lines of measurement programs. Only closer collaboration between observationalists and modellers can lead us to understand, and then simulate, this huge variability.

1.2. Particularities of equatorial oceans

If we leave out astronomical forces, oceanic fluctuations are directed by the influxes of heat from the atmosphere and of momentum imparted by the wind. *The relative importance of these influxes* on the surface layers differentiates fundamentally according to latitude.

In medium and high latitudes, local thermodynamics is dominant, hence the success of *uni-dimensional models to simulate the thermal* variations in surface layers (LACOMBE, 1973). Moreover, these areas seem dominated by the presence of meso-scale vortices. These transient movements, with very small phase speed, contain vast amounts of kinetic energy, often exceeding those of the mean flow. Their high number and the immediate impossibility to link them to any direct origin have led us to consider them as large scale turbulence. So it seems that spectral techniques are most adapted to integrate them in a model.

In lower latitudes, it appears that uni-dimensional thermodynamic models do not fit. MERLE (1980a), in particular, finds that, on a seasonal time scale, the variations in thermal content of the equatorial Atlantic Ocean are ten times greater than the local variations of heat exchange between the atmosphere and the ocean. Therefore, a very important redistribution of heat through purely equatorial dynamics seems to happen. On a large scale these dynamics appear to be directly linked to the wind. The most spectacular example of this occurs in the Indian Ocean when the Somali current reverses with the turn of the monsoon. It seems, then, that dynamic oceanic models directly forced by wind are better adapted to lower latitudes, than are thermodynamic ones. The ability of the corresponding oceans to respond clearly and coherently to the low frequency wind forcing greatly eases the study of their variability. Furthermore, apart from a few occasional cyclones, the prevailing trade wind conditions over the tropics are far more stable and regular than the wind conditions of higher latitudes.

These very particular equatorial dynamics, we shall see, are linked to the cancellation and inversion of the Coriolis force on passing the equator. This singularity also explains an oceanic upwelling and a countercurrent along the equator. This subsurface current belongs to a set of triple-branched zonal countercurrents (KHANAICHENKO, 1974) transporting considerable amounts of energy from west to east. As opposed to those in the temperate oceans, all the countercurrents as well as the ocean-surface and coastal currents in the equatorial oceans are very swift and narrow. Therefore, the equatorial oceans are strongly baroclinic, as suggested also by the presence of a marked, almost permanent thermocline. This barocline character is also important at greater depths, as evidenced in the recent discovery of multiple zonal jets confined to the equator. LUYTEN and SWALLOW (1976), in the Indian Ocean, were the first to observe these jets with the help of a new floating profiler. Measurements in the Pacific by HAYES and MILBURN (1980) and ERIKSEN (1981) and in the Gulf of Guinea by WEISBERG and HORIGAN (1981) suggest the presence of such jets in other equatorial oceans. These jets may have a period of a few months to one year and a vertical scale of a few hundred meters, and could account for most of the energy in the deep equatorial oceans.

Theory and observations show that internal waves with periods of a few minutes to a few hours do not really differ widely according to latitude. On the other hand, in low and medium frequency ranges the dynamic effects of the cancellations at the equator of the Coriolis force and the symmetrical gradient of the planetary vorticity turn the equator into a very effective wave guide. This has been demonstrated by equatorial theory (MOORE, 1968 ; MOORE and PHILANDER, 1977) : the equations are linearized (perturbation method) and allow the separation of the vertical structure from the horizontal one. Thus, the equatorial ocean is divided into barotropic and baroclinic modes along the vertical structure, and into horizontal modes. These horizontal modes are represented by Hermite oscillating functions coupled to an exponential decay that corresponds to the equatorial trapping. This trapping has no repercussion on the barotropic mode, and so this mode must be treated as a global ocean phenomenon and not specific to the equatorial area. The solutions therefore obtained are composed of different types of equatorial waves:

- Inertia-gravity waves, with phase and energy propagate either eastward or westward, with a period of one day to one week.
- Mixed Rossby-gravity waves, also called Yanai waves, with eastward group velocity and either eastward or westward phase velocity.
- Rossby waves with westward phase velocity and with periods greater than one month divided into dispersive waves of short wavelength (a few hundred kilometers) with eastward group velocity and nearly non-dispersive waves of long wavelength (a few thousand kilometers).
- Non-dispersive Kelvin waves with eastward phase and group velocity.

These equatorial waves cover a continuous range of periods from one day to one year. On the contrary, in mid-latitudes, there is a spectral gap between the only two groups of free waves possible: inertia-gravity waves (inertial period or less) and Rossby or planetary waves (period of a few months to a few years). In the intermediate frequency band only forced waves are possible (PHILANDER, 1979a). So in mid-latitudes there are no free long waves going east, which partly explains the accumulation of energy on the western coast of the oceans. On the contrary, the equatorial wave guide affords an energy transfer path to the eastern coast of the oceans.

Equatorial areas are also characterized by their ability to rapidly respond to any change in wind stress, this ability being a consequence of the wave guide. Rossby waves play a major role in such an adjustment, because they help establish the horizontal pressure gradient that counteracts the wind stress. Because of the great phase speed of equatorial baroclinic modes, this adjustment takes only a few months. However, in high and mid-latitudes it is a matter of up to a decade, and the corresponding variation of a basin-wide pressure gradient would also take a decade. Therefore, the following horizontal redistribution of heat would be extremely slow. In equatorial zones the adjustment time scale is of the same order as the wind variation time scale, which is obviously not at all the case in the mid and high latitudes (LEETMAA *et al.*, 1981). This approach partly explains why wind forced models work better for the lower latitudes than mixed layer unidimensional thermodynamic models, which are better adapted to higher latitudes.

Another interesting feature of equatorial waves that propagate rapidly east or west is their ability to radiate energy outside the wind forcing area. This energy can react very quickly and strongly over distant regions. This phenomenon, known as remote forcing, is the object of most of our present studies. Moreover, this mechanism could be at the origin of deep equatorial jets, as, according to MCCREARY (1984), equatorial waves also radiate downward, and give rise, after any eventual reflections on the meridional boundaries, to multiple deep equatorial jets. This theoretical study seems corroborated by recent observations by LUYTEN and ROEMICH (1982) in the Indian Ocean.

Variations in the wind intensity in the equatorial strip and of the wind stress curl in non-equatorial zones are responsible for most of these equatorial waves, but instability between currents or rapid changes in air pressure can also induce shorter inertia-gravity waves (Philander, 1978 b). So far only the latter waves have been definitely observed. The direct detection of long equatorial waves is blurred by high frequency interference in the surface layers, by local non-oscillatory phenomena (possibly of thermodynamic or thermohaline origin), by the lack of long-term measurements and by the non-sinusoidal character of these waves. Besides plausible direct evidences found by KNOX and HALPERN (1982), ERIKSEN *et al.* (1983) and LUKAS *et al.* (1984), indirect methods, such as those presented further on, are another way to support the evidence of long equatorial waves.

1.3. Climatic and economic interests of the equatorial oceans

Tropical zones are characterized by an accumulation of solar heat in the surface layers all year long (HASTENRATH and LAMB, 1977). They are the only zones of the oceans where the thermal ocean-atmosphere balance is largely positive, unlike the middle and high latitude zones So there are important energy transfers from the tropics to the poles via interacting ocean-atmosphere processes and marine advection. But a mean transfer also exists between the two hemispheres through the tropical areas as the energy balance of each hemisphere is not at equilibrium (OORT and VONDER HAAR, 1976). Large scale, low frequency fluctuations in these transfers are at the origin of climatic variations on our planet. Recent numerical models (SHUKLA, 1975 ; REITER, 1978) demonstrate the importance of equatorial currents and SST in the mechanisms of climatic variations of not only the tropics but also of the higher latitudes.

BJERKNES (1966-1969) was the first to envisage such a large scale ocean-atmosphere interaction in the tropical Pacific. He suggested that the Walker convective circulation cell in the equatorial plane responds directly to variations in the SST gradient along the equator. The gradient is the result of a thermocline deep in the western part of the equatorial basin and close to the surface in the eastern part. This representation is completed, for the north-south exchanges, by the Hadley meridian cell, driven by the thermal differences between tropical and mid-latitudes. WYRTKI (1975) picked up this idea emphasizing the dynamic response of the ocean to the wind. Indeed, the seasonal and interannual variations of the thermocline's depth in the equatorial plane seem immediately linked to the intensity of the zonal winds, which are the lower part of the Walker cell. This example of the ocean-atmosphere coupling was modelled by MCCREARY (1983) and could even have some influence on the North Pacific and North American climates (BJERKNES, 1966).

The tropics are also areas that often respond catastrophically to variations of SST. The preceding scheme has been proposed by BJERKNES as a possible explanation of the well-known « El Nino » phenomenon of abnormal accumulation of warm water along the Ecuador and Peru coasts. This event induces devastating rains along these coasts. In the tropical Atlantic a similar phenomenon seems to appear (HISARD, 1980 ; MERLE, 1980 b), which brings terrific rains along the coasts of the Gulf of Guinea (HOOKEY, 1970) and Angola (HISARD and PITON, 1981). As a matter of fact, the SST influences the rainfall intensity via the control of humidity and stability of the lower atmosphere layers. In the northern part of the tropical Atlantic, abnormal SST might have an important effect on cyclogenesis (NAMIAS, 1969). On a larger scale it seems that there is some link between the SST and the droughts of the Sahel (LAMB, 1978) and of northern Brazil (MARKMAN and MCLAIN, 1977 ; HASTENRATH, 1976).

We know the important consequences « El Nino » has on the climate of the coasts of Ecuador and Peru. If the corresponding upwelling were to halt, it would entail a sharp drop in the world's biggest anchovy population, closely followed by an important decrease in the number of seabirds, which in turn means a loss in the amount of guano available. Indeed, upwelling plays an active part in fertilizing the euphotic zone by bringing up nutrient salts and leads to an increase in productivity via the food chain. Upwelling also induces important changes in physical parameters, such as SST and depth of the thermocline, which in turn influence the concentration of fish (EVANS *et al.*, 1980). The tropics are the areas where upwelling is most intense. The resurgence of cold waters is almost permanent along the north-eastern and southeastern coasts of the tropical basins and is seasonal in the eastern part of the equatorial strip along the coasts and along the equator.

The importance of the Atlantic equatorial upwelling as a fertilizing agent has been described by VOITURIEZ *et al.* (1982). The seasonal upwelling in the Gulf of Guinea is at the origin of the formation of thermal fronts, which favor the concentration of tuna fish (STRETTA, 1977). This coastal upwelling also spreads nutrients of fluvial origin and plays a part in the importance of anchovy and sardinella catches (BINET, 1982). Further south, a phenomenon similar to « El Nino » can disrupt anchovy and sardinella fishing off the coast of Angola (HISARD and PITON, 1981).

To conclude, it seems that tropical oceans either directly or indirectly determine climatic variations, which entail important economic consequences. The greater part of these variations can be predicted only by coupled ocean-atmosphere models, but the highly non-linear character of this coupling cannot, at this time, guarantee the results of such models. In the meantime, oceanographers are trying to better understand the physics of the response of the ocean to the various forcings.

1.4. **Features of the tropical Atlantic and, in particular, of the Gulf of Guinea**

(a) *The tropical Atlantic*

We have seen that — concerning climatic, economic and human disasters — the tropical Pacific has the greatest effect on its southeastern coasts while the tropical Atlantic has its greatest influence further inland: the Sahel drought. These two tropical oceans differ in many more aspects — the major one being their size, with the Pacific Ocean three times wider than the Atlantic Ocean. Because the equilibrium time scale of tropical oceans to low frequency wind forcing is related to the time a long baroclinic wave takes to cross the basin, this time scale should be greater in the Pacific than in the Atlantic. This might explain a predominance of the seasonal signal in the equatorial Atlantic (MERLE *et al.*, 1980) and of the interannual signal in the equatorial Pacific (WYRTKI, 1975 ; HICKEY, 1975 ; BUSALACCHI, 1982). In spite of this, recent results on a linear model forced by periodic winds (CANE and SARACHIK, 1981) suggest that the difference in the response might be due to the differences in wind conditions of the two oceans. The annual wind cycle is more obvious in the tropical Atlantic than in the tropical Pacific (PHILANDER and PACANOWSKI, 1981 a ; WYRTKI, 1975 ; RODEN, 1962). On the other hand, the semi-annual wind cycle and its responses exist in the tropical Atlantic (BUSALACCHI and PICAUT, 1983 ; MERLE and LE FLOCH, 1978) as in the tropical Pacific (BUSALACCHI and O'BRIEN, 1980 ; MEYERS, 1979 b). However, they are much less intense in these oceans than in the Indian Ocean, where the main feature is the reversal of the monsoons.

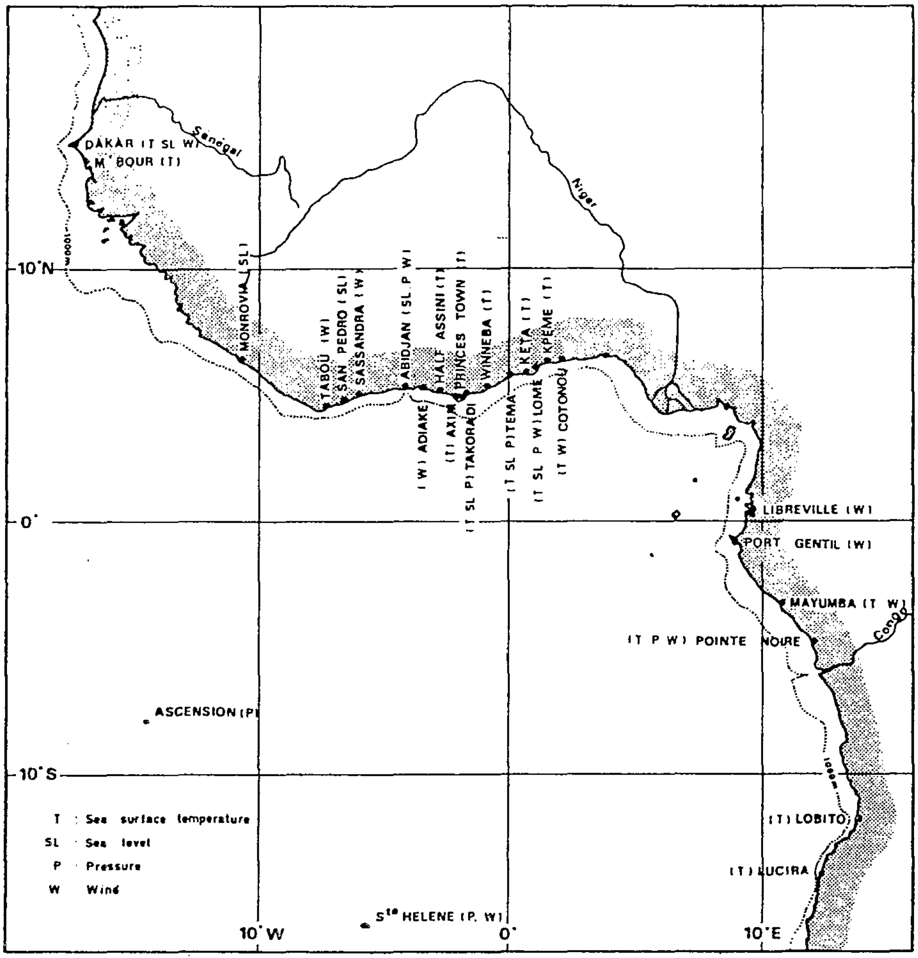

FIG. 1. — The Gulf of Guinea and the coastal stations (from VERSTRAETE *et al.*, 1980)
Le Golfe de Guinée et les stations côtières (d'après VERSTRAETE et al., *1980)*

(b) *The Gulf of Guinea*

Contrary to the other parts of the equatorial Atlantic, which are mostly under the influence of strong zonal winds coming from the northeast and southeast trades, the Gulf of Guinea is mostly under the influence of mean southerly monsoon winds. This region constitutes one third of the equatorial Atlantic and has come under close oceanographic and meteorological scrutiny owing to French presence for many years. For example, all along its coast, water sample and SST measurements are taken daily at coastal stations, some of which have been in operation for more than twenty years (Fig. 1). The main feature of this eastern part of the equatorial Atlantic is a surfacing thermocline, unlike the western part. As a result of the thermocline's movements, mixing up processes induce important variations in SST (5° to 7° against 1-2° in the west), which as previously mentioned, have great climatic, economic, and social consequences. Because the thermocline exists so very close to the surface, tuna are vulnerable to modern fishing techniques. This is why the greater part of the tropical Atlantic tuna catch comes from the Gulf of Guinea (EVANS *et al* , 1980 ; FONTENEAU and CAYRÉ, 1983).

The seasonal displacement of this thermocline is linked to an equatorial and coastal upwelling phenomenon, not yet clearly explained by the classical concepts of Ekman's theory and/or of advection (BERRIT, 1976 ; HOUGHTON, 1976 ; BAKUN, 1978 ; VOITURIEZ, 1980). One of the main results of present studies has been to establish that a significant part of this phenomenon is due to zonal winds outside the Gulf of Guinea, whose energy is transmitted to the Gulf via equatorial waves. These seasonal variations are modified by important high frequency fluctuations, which could be due to

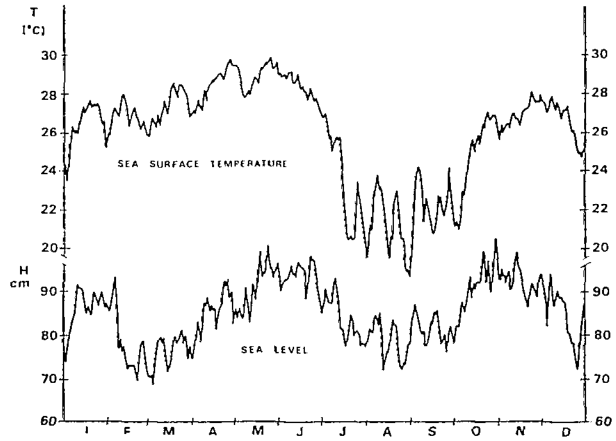

FIG. 2. — Daily variations of SST and sea level during 1974 at Tema (from PICAUT and VERSTRAETE, 1979)
Variations journalières de température de surface et de niveau moyen en 1974 à Téma (d'après PICAUT *et* VERSTRAETE, *1979)*

equatorial waves or to coastal waves (Fig. 2). Energy can also be trapped via shelf waves by a sharp discontinuity of the ocean floor (continental shelf break) or by a regular slope of the ocean floor (continental shelf). Because the Gulf of Guinea coasts are always close to the equator, the region is favorable to the existence of equatorial topographic baroclinic and barotropic waves. The existence of an east-west oriented coast, unique in equatorial zones, may induce an extra mode of equatorially-trapped waves in the shape of an west-going Kelvin wave, trapped along the coast (HICKIE, 1977 ; PHILANDER, 1977). Finally, from the same, rather theoretical point of view, the fact that the bottom of the Gulf of Guinea is flat tends to lead us to think that vertical standing modes can establish themselves more easily in the eastern part of the equatorial Atlantic than in the western part, where the floor is very uneven (GARZOLI and KATZ, 1981).

The presence of an Oceanographic Research Center (ORSTOM) in Abidjan, i.e. on the east-west oriented coast and only a few degrees from the equator, is a major advantage for the study of such equatorial phenomena.

1.5. Introduction to the present study

The object of our present study is to deal with oscillations whose periods are superior or equal to that of the semi-diurnal tide. We have disregarded high frequency internal waves, i.e. waves of periods from a few minutes to a few hours. Though they have been systematically observed since 1968 (TREBERN-ETIENNE, 1971) they present no basic difference from waves at higher latitudes. In the large scale models we used, they are considered as turbulence, and parameterized as such.

The frequency domain of our study is divided into two bands. The first, defined by us as the medium frequency band, from semi-diurnal to four month long periods, comprise all oscillations we have observed at fixed points, either from a research ship or from a coastal station. The second band, defined by us as the low frequency band, deals with the seasonal and interannual cycles. There is no clear distinction between the two bands. We have shown (PICAUT, 1983) that the seasonal cycle was perfectly reconstructed with the use of the first five harmonics of the annual cycle. Energywise, only the first three are relevant, and, if one can easily imagine annual and semi-annual events in the ocean, the concept of a quarterly oceanic wave is problematic (PICAUT *et al*, 1978).

We have centered our medium frequency study mainly on shelf waves forced by the tide (semi-diurnal and fortnightly luni-solar) and the atmosphere (period of 45 days). The last chapter, on the other hand, is concerned mostly with the dynamics of coastal and equatorial upwellings on the seasonal and interannual time scale.

We must note that a good part of our observational basis consists of SST in the Gulf of Guinea where the thermocline is always close to the surface and that we are mostly looking at the dynamics involved in the variability at all these frequency bands Therefore, we have to keep in mind that, in addition to dynamical movements of the surfacing thermocline, some thermodynamical processes are needed to mix up the surface layer in order to induce SST changes.

2. MEDIUM FREQUENCY VARIATION

2.1. Internal semi-diurnal tide

The tide is the perfect example of oceanic response to oscillatory forcing. The barotropic case was mathematically formulated by Laplace as early as 1776, but it was not until 1940 that stratification was added to these equations (HENDERSHOTT, 1981). Whereas the phenomenon of barotropic tide has been common knowledge for centuries, it was not until the beginning of the century that Nansen made the first observations of internal tides. Some fixed point measurements made during the Meteor cruise and by VARLET (1958) suggest their existence in the Gulf of Guinea.

In 1973, we went to sea about a dozen times on board the RV Reine Pokou belonging to the Ivory Coast Oceanographic Research Center, in order to gather data on the internal variations induced by the

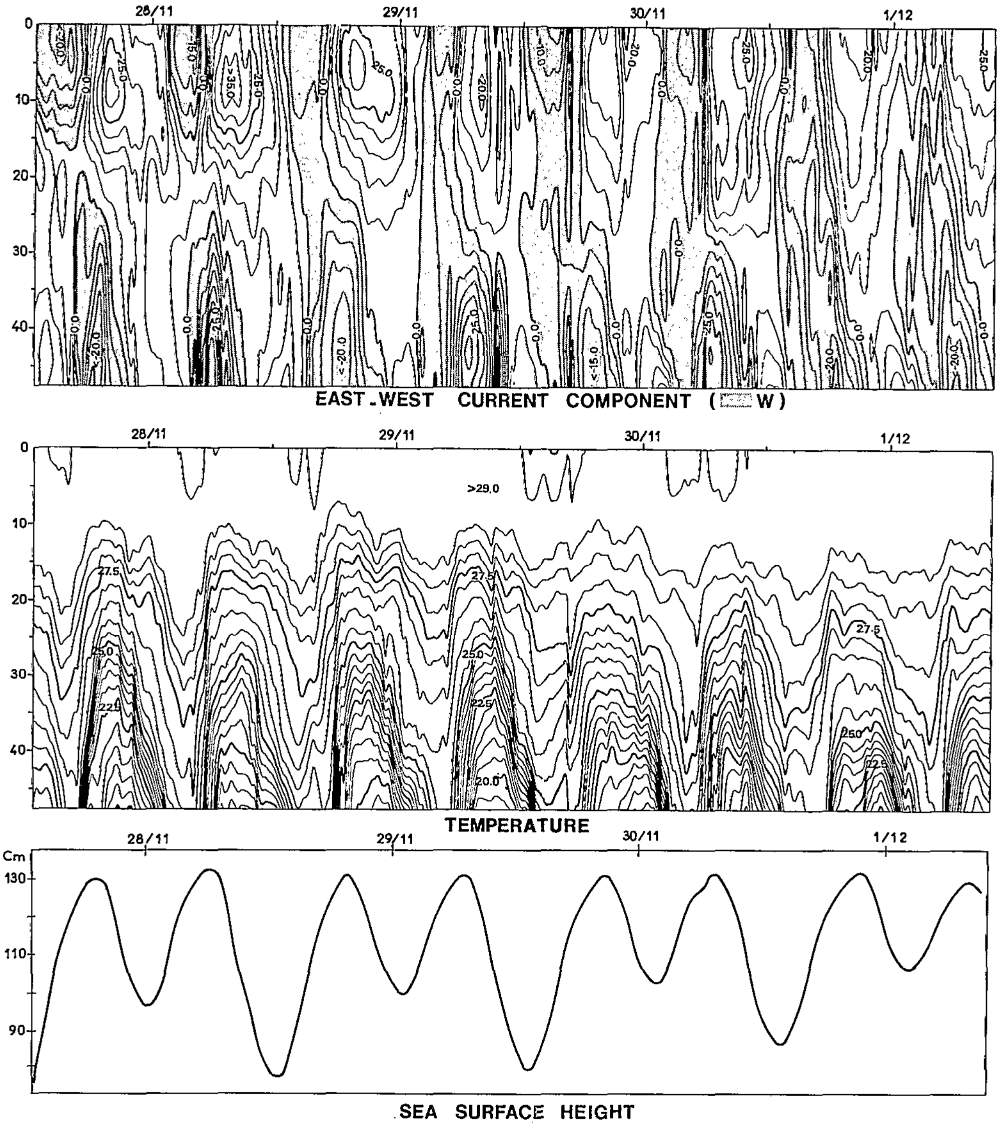

FIG. 3. — Internal tides observed during four days in a water depth of 52 m from 298 current and temperature profiles and associated mean sea level at the coast (from PICAUT and VERSTRAETE, 1979)

Marée interne observée pendant quatre jours sur un fond de 52 m au large d'Abidjan à partir de 298 profils de courant et de température et niveau moyen correspondant mesuré à la côte (d'après PICAUT *et* VERSTRAETE, *1979)*

big underwater canyon off Abidjan, called "Trou sans Fond." Some of the measurements from height fixed points, either on the continental shelf or on the shelf break, establish the permanence and high amplitude of internal-tide waves. Thus, one finds that at a depth of 200 meters the isotherms shift mainly semi-diurnally over 50 meters or more, and at a depth of 50 meters, about 30 meters. During the last two experiments, a current profiler, kindly loaned by the University of Miami, was in constant use, and led to the drawing up of 450 current and temperature profiles. Figure 3 shows the results of the last fixed point. A correlation strongly emerges between the vertical movement of the isotherm, the current component parallel to the coast, and the mean sea level measured a few miles out. The temperatures on the ocean floor can vary by as much as 6° in a few hours. The oscillations of the currents, virtually in opposition phase between the surface and bottom layers, suggest the predominance of the first baroclinic mode.

This set of data and preliminary calculations have been developed by PARK (1979). His main results can be summarized as follows: If the slope is not steep, the linear theory of internal waves explains most of these variations. If the slope is steep the movement of water over the slope due to the barotropic tidal current might be important. One should not entirely disregard the baroclinic movements induced by the barotropic tidal current through the horizontal density gradient which balances the Guinea Current. The rearrangement of the mean stratification in accordance to marine seasonal changes (MORLIÈRE and RÉBERT, 1972) seems to influence the internal features of these oscillations. During the warm season, in particular, an analysis of the currents shows that the first baroclinic mode is strongly predominant and is equal in amplitude to the barotropic mode. The adaptation of PRINSEBERG's model (1971) to the Ivory Coast's continental shelf and of CAVANIÉ's (1969) to the canyon "Trou sans Fond" show these internal waves can be generated by the tidal current action on the shelf break and the edges of the canyon.

In relation to the spectral distribution of these internal waves, PARK (1979) points out the presence of weak diurnal oscillations. From a six-month series of measurements with a thermistor chain, PICAUT and VERSTRAETE (1979) managed to separate the semi-diurnal internal waves M_2 and S_2, the first being of course the major one.

These internal tides, also found off the coast of the Gulf of Guinea, could have caused errors in the interpretation in hydrological measurements (DEFANT, 1950), which is why they have been filtered where possible in the rest of this study. But they do seem to be an important source of internal ocean stirring and mixing. WUNSCH (1975) finds that at least 10 % of barotropic tidal energy is transferred to internal tides, which, in comparison, is similar to the energy input by the general mean circulation.

These oscillations are also remarkable as their interaction can affect the phytoplankton, hence the food chain (KAMYKOWSKI, 1974). It seems they influence directly the distribution of fish. An experiment involving 24 trawling operations in 48 hours surrounded by four days of continuous data collecting tended to prove that the movement of some fish followed the temperature variations due to the internal tides (CAVERIVIÈRE and PICAUT, personal communication, 1983).

2.2. Coastal waves

Thanks to the first coastal station at Lome in Togo, it appears that the SST can vary as much as 5° in less than a week (see Fig. 2). The first spectral analysis on these temperature time series and on a time series of tidal observations at Abidjan enable us to point out energy peaks in the 3 to 60 day period band. With J. M. VERSTRAETE, we inventoried the information of as many stations as possible along the coasts of Togo, Benin, Ghana and Ivory Coast, and the other ORSTOM centers in Dakar (Senegal) and Pointe-Noire (Congo) did the same. The chronological series of 27 stations (Fig. 1), usually consisting of daily measurements of sea surface temperature, average atmospheric pressure, mean sea level and wind observations, were thus systemically analyzed. At the same time, we maintained a thermistor chain at a depth of 65 m off Abidjan for about six months. The corresponding results on figure 4, drawn up after we eliminated all fluctuations due to the internal semi-diurnal tide, show that these medium frequency oscillations affect the entire water column. These results also show that the northern summer upwelling is triggered at depth as early as mid-May, creating a maximum surface cooling (21°) at the end of July.

The chronological series were treated statistically through methods like spectral analysis, cross correlation, Fourier decomposition, tidal harmonic analysis, pass band filtering, and complex demodulation. These analyses indicated energetic oceanic coastal oscillations in the 3 to 9 day period band, in the 13 to 15 day period band, and 40 to 50 day period band (PICAUT *et al.*, 1978 ; VERSTRAETE *et al.*, 1980).

(a) *3 to 9 day periods*

- An oscillation of about 3 days seems forced by the wind.
- An oscillation in the trade winds of 3 to 6 days (KRISHNAMURTI and KRISHNAMURTI, 1980), probably linked to African atmospheric waves going westward (ARNOLD, 1966), could force an oceanic wave in the same period range. HOUGHTON (1979) and McGRAIL (1979) picked out the same oscillation from current measurements on the continental shelf off Ghana, Liberia and Sierra Leone. It is important to bear in mind that the inertial period in the northern coast of the Gulf of Guinea is of this same order.
- The atmosphere could force a 9 day period oceanic wave. HOUGHTON (1979) with current measurements isolates such an oscillation which decreases as it nears the ocean floor. BEER (1978 a), in a study of barotropic shelf waves, indicates this wave could be the second barotropic mode.

(b) *Semi-monthly periods*

In 1974, a very definite semi-monthly oscillation appeared in the daily SST record during the upwelling season, when the thermocline is nearest the surface.

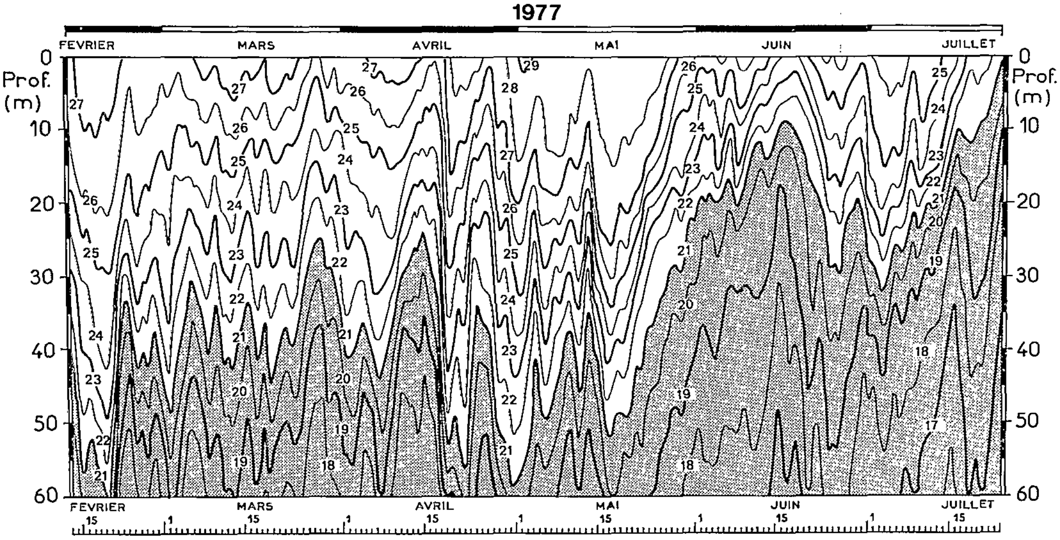

FIG. 4. — Variation of the thermal structure in a water depth of 65 m off Abidjan from February 11 to July 25, 1977, derived from low pass filtered SST and thermistor chain measurements (from VERSTRAETE and PICAUT, 1983)

Variation de la structure thermique sur un fond de 65 m au large d'Abidjan du 11 février au 25 juillet 1977, à partir de données de température de surface et d'une chaîne à thermistance après élimination des oscillations dues aux marées internes (d'après VERSTRAETE *et* PICAUT, *1983)*

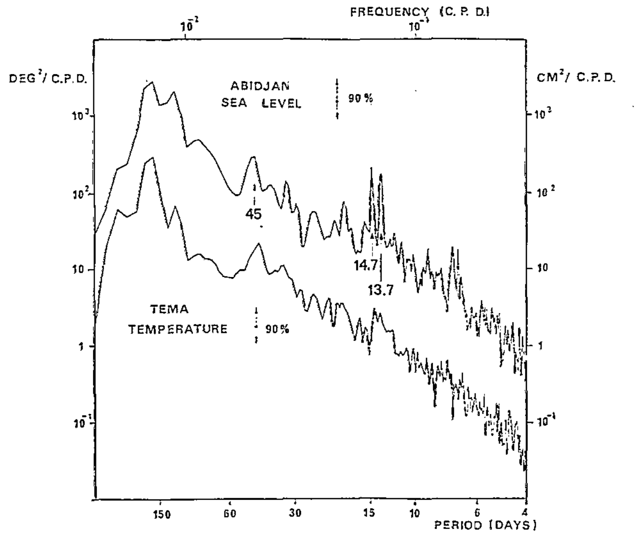

FIG. 5. — Autospectra of 10 years of mean sea level at Abidjan and 13 years of SST at Tema (from PICAUT and VERSTRAETE, 1979)

Spectre de 10 années de niveau moyen à Abidjan et de 13 années de température de surface à Téma (d'après PICAUT *et* VERSTRAETE, *1979)*

HOUGHTON and BEER (1976), using measurements taken at the Ghana and Togo stations over the same period, show this oscillation propagates westward at an average speed of 64 cm/s. At the same time, PICAUT and VERSTRAETE (1975), with a spectral analysis of all the time series of SST, found an energetic peak, at a period of about 15 days, propagating along the northern coast of the Gulf of Guinea at a mean speed of 75 cm/s. We both carried this line of research further and gathered as much mean sea level information as possible concerning the area and proved the oscillation exists all year long in the mean sea level. Most of all, we established that it is composed of two waves (Fig. 5): One is the lunar fortnightly tide Mf (13.66 day period), which has a constant phase all along the coast. The other wave has a period of 14.76 days, which is the period of the luni-solar fortnightly tide Msf; this wave propagates westward for at least 1 500 km along the north coast of the Gulf of Guinea at a mean phase speed of 53 cm/s (Fig. 6) and a wavelength of 675 km (PICAUT and VERSTRAETE, 1979). These waves have important effects on the thermal structure and give rise to strong vertical oscillations of the subsurface isotherms all year round.

Because of the weakness of the luni-solar semi-monthly astronomic forcing, we inferred the Msf wave was, most probably, the result of a non-linear interaction between the M_2 and the S_2 semi-diurnal tide waves. We have seen that the M_2 and S_2 internal tides probably exist along the entire coast of the Gulf of Guinea, so they could force a 14.76 day period wave, via a nonlinear process. Yet it seems

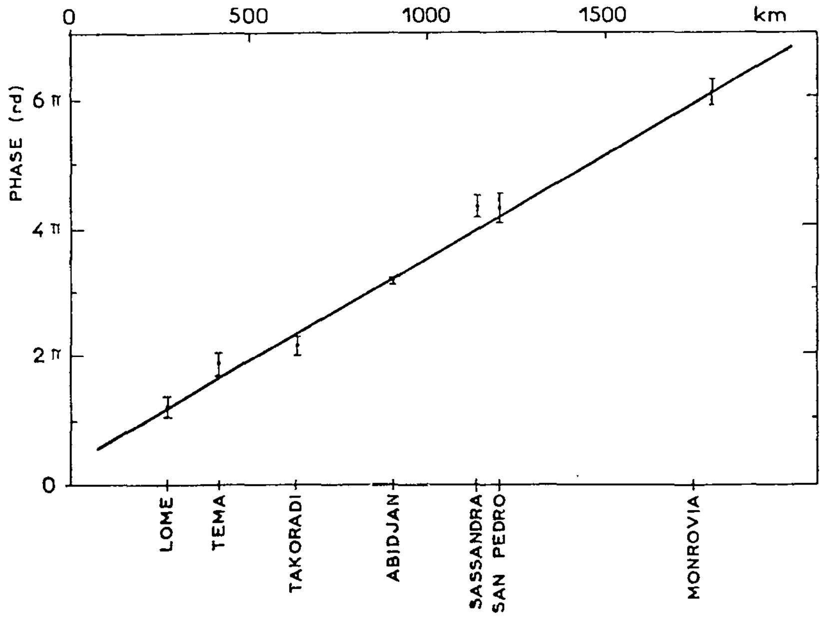

FIG. 6. — Sea level phase variation of the 14.7 day wave along the northern coast of the Gulf of Guinea (from PICAUT and VERSTRAETE, 1979)

Variation de la phase de l'onde de 14,7 jours de période le long de la côte Nord du Golfe de Guinée (d'après PICAUT *et* VERSTRAETE, *1979)*

difficult to ascribe a 675 km wavelength oscillation to be the result of local forcing of 15 and 10 km wavelength oscillations. We found it easier to hypothesize a nonlinear interaction between the barotropic tides M_2 and S_2 in the area of the Gulf of Guinea, where the continental shelf is shallowest and widest, i.e. in its northeast corner. A free wave could then be generated, providing a typical example of remote forcing. This wave could be either a topographical shelf wave (PHILANDER, 1979 a), an internal Kelvin wave (HOUGHTON and BEER, 1976) or an equatorial shelf wave (MYSAK, 1978a-b; PICAUT and VERSTRAETE, 1979). Recent analysis of current measurements by HOUGHTON (1979) reveal the energy of this wave seems to be trapped under the thermocline; HOUGHTON believes that WANG and MOOERS's (1976) model of the hybrid topographical shelf wave modified by stratification is most appropriate. Though there remains contradictions between all these various models, the wave cannot be barotropic as it appears as important fluctuations in the isotherms. On the other hand, PICAUT and VERSTRAETE (1979) showed that, when the stratification on the continental shelf is altered with the onset of the upwelling season, the speed of this wave is unchanged. CLARKE and BATTISTI (1983), using a realist topographical model with continuous stratification on a ß-plane, found that the observed wave coincides with the calculated second mode and, most of all, that its speed is related to stratification only under 150 m. As stratification is almost stable under this level through all the seasons, this last model observed explains the constant speed.

(c) *40 to 50 day period*

Before going on to this frequency band, we want to mention a low energy wave of a 31.8 day period corresponding to the monthly Msm tide (VERSTRAETE *et al.*, 1980).

Our first studies on the time series of the Gulf of Guinea stations led us to uncover a 40 to 50 day period wave (PICAUT and VERSTRAETE, 1976). Spectral analysis of the mean sea level corrected from the barometric effect and of the SST in various stations along the Gulf of Guinea coast shows a 90 % significant energy peak in this period band. Computations of phase by cross-spectrum and cross-correlation after pass band filtering indicate this wave is probably stationary along the north coast of the Gulf of Guinea. Energy peaks around the same frequency band in air pressure, sea level and wind measurements suggest this coastal wave could be forced by the atmosphere. This mode of generation seems confirmed in the spectral graph of currents by HOUGHTON (1979) where a decrease of the corresponding peak is observed as the measurements near the ocean bottom.

Madden and Jullian (1971, 1972) show the existence of an atmospheric wave of the same period above the Pacific and Indian oceans. This oscillation seems to be the result of a large scale atmospheric cell flow, propagating eastward in the equatorial plane, and it could generate an equatorial Kelvin wave in the ocean (Philander, 1977). But as we shall see in the next paragraph, there seems to be no Atlantic Ocean equatorial wave in this period range. Further study is needed to understand the relation between the atmospheric wave and the oceanic coastal wave we have discovered.

For further reference on coastal waves, let us mention Portonalo's (1981) work with all the data from the Senegal coastal stations, although this work is about an area somewhat outside that which concerns us. SST in this region appears to be partly forced by low frequency displacement of the Intertropical Convergence Zone (ITCZ) and by medium frequency variation of the wind direction.

2.3. **Oceanic waves**

Our studies of medium frequency variation were made mostly from coastal stations, so we cannot directly deal with oceanic waves in the equatorial Atlantic. Yet it appears interesting to sum up the main advances in the field. In most cases they were solely due to long-term moorings, GATE being the first example with three months of moorings in the equatorial Atlantic. These and ensuing works have turned up evidence of energetic movement in the 3 to 5 day period band, in the 9 to 10 day band, in the 14 to 18 day band and in the period of about one month.

(a) *3 to 5 day period*

We already know there are ITCZ oscillations covering the 3 to 6 day period band. They could induce a barotropic response by pressure forcing or a baroclinic response by wind forcing (Beer, 1978b). The GATE measurements permitted the discovery of an oscillation dynamically consistent with an internal equatorial gravity wave whose energy seems to be derived from mean currents (Weisberg *et al.*, 1980). Though similar waves appear to correspond to a resonant mode in the Pacific (Wunsch and Gill, 1976), this is not the case in the Atlantic (Philander and Duing, 1980). Study of the thermocline movement from the measurements taken by three inverted echo sounders moored near the equator, in the western part of the basin, points to a common energy peak at a period of about 3.75 days. Reference to the dispersion diagram rules out a free wave, but an analysis of coherency with the wind deduced from inverted echo sounders shows this oscillation could be an inertia gravity wave forced by the atmosphere in the western part of the ocean (Garzoli and Katz, 1981). Similar measurements at 4° W suggest this wave trapped at the equator could be a free one in the eastern part (Miller, 1981).

(b) *9 to 10 day period*

As a result of current measurements taken near the equator at 26° and 28° W, Weisberg *et al.* (1980) found a 9 to 10 day period oscillation. This wave propagates westward and upward which means a sinking of energy. As concerns dynamics, it could coincide with the second meridional mode of an internal gravity wave, but Philander (1978 a) inclines rather for a mixed Rossby-gravity wave. This wave could be forced by the atmosphere, and Bubnov *et al.* (1980) found it in most of the surface measurements taken at two 10° W moorings. In the surface layer, it is blurred by meanders of the Equatorial Undercurrent.

(c) *14 to 18 day period*

Neumann and William (1965), using a subsurface drogue, were the first to notice meanders at the equator. Repeated measurements by Rinkel (1969) at 8° W on the equator uncovered a 14 day period oscillation in the Equatorial Undercurrent. More recently, Le Floch (1972) found that the maximum salinity in the Gulf of Guinea associated with this undercurrent regularly swings, approximately in a 16 day period, 40 miles either side of the 0°15' S parallel.

Satellite and ship measurements contributed much data on the meanders between 0° and 30° W (Duing *et al.*, 1975). They oscillate over a period of 16 days at 1° from the equator and occur mainly in the 200 m surface layer. They propagate upward at an average phase speed of 50 m/day and westward at a speed around 1.35 m/s, which gives a wavelength of about 1 850 km. They also induce an asymmetry in zonal current component (Duing and Hallock, 1980).

Monin (1972, quoted by Bubnov *et al.*, 1980) proposed an inertial model of the meanders in the Equatorial Undercurrent which period coincides with the period measured. Direct wind measurements from satellite observations of cloud drift indicated a 15 day period fluctuation in the trade winds propagating west with a 4 000 km wavelength (Krishnamurti and Krishnamurti, 1980). The atmosphere, therefore, could force these meanders as a mixed Rossby-gravity wave, but there remains the discrepancy of the wavelengths between the oceanic and atmospheric waves. HALLOCK (1980) determined from a baroclinic model that the dominant response to an irregular meridional wind is a Rossby-gravity wave whose features resemble those of a 14 to 18 day period observed. Finally, PHILANDER and DUING (1980) suggest the meanders, despite their relative stability, could rapidly increase under major forcing of a similar scale.

(d) *30 to 32 day period*

By way of surface moorings from the RV Passat at 10° W and the RV Trident at 16° and 28° W, WEISBERG (1980) notes the predominant 16 day period in the surface layer interacts with a 32 day period fluctuation. The latter appears well under the Equatorial Undercurrent. BROWN (1980), during the GATE experiment, found a similar oscillation in SST observed by satellite around 3° N where the horizontal thermal gradient related to zonal currents is highest. Longer subsurface measurements in the Gulf of Guinea detected this oscillation in the meridional component of currents, allowing an accurate definition of its characteristics (WEISBERG *et al.*, 1979). Its mean period is of 31 days, and it moves westward and upward with wavelengths of 1 200 km and 100 m respectively. The associated energy propagates eastward and downward at a group speed of 16 cm/s and 0.014 cm/s respectively. This mixed Rossby-gravity wave, modulated by seasonal variations, is trapped at the equator with an exponential decay of 210 km.

Surface instability, between the North Equatorial Counter Current, radiating eastward and downward, might form this wave (PHILANDER, 1978b). This could explain the wave's importance in the deep layers of the Gulf of Guinea, where it is already responsible for two thirds of the variability in the meridional component (WEISBERG *et al.*, 1979).

All these studies reveal the existence and importance of trapped equatorial and coastal waves in the equatorial Atlantic. Very often these waves are energetic and seem to have an influence on mean currents. A determination, by CRAWFORD and OSBORN (1980), of the kinetic energy involved in the mean movement shows that the energy contributed by the wind is lost partly in turbulence and partly in the establishment of the zonal pressure gradient. The amount of energy transferred to oscillations and meanders is significant but difficult to estimate precisely. The main changes in the zonal pressure gradient generated by the wind are the dominating feature of the seasonal variations in the equatorial Atlantic (KATZ *et al.*, 1977; MERLE, 1980), variations which will be studied in the following chapter.

3. LOW FREQUENCY VARIATIONS: RESPONSE TO REMOTE FORCING IN THE GULF OF GUINEA

3.1. **The upwelling in the Gulf of Guinea**

Thanks to the Oceanographic Research Centers (ORSTOM) in Ivory Coast, Senegal, and the Republic of Congo, and also to the Ghana Fishery Research Unit, we now know the seasonal variations in the Gulf of Guinea quite well. Four marine seasons have thus been evidenced in the top layer (BERRIT, 1958; MORLIÈRE, 1970): one long warm season from February to May, one long cold season from June to October, one short warm season from November to mid-December, and one short cold season from mid-December to January. The Fourier decomposition of this seasonal cycle and the spectral analysis of the longest chronological series (LE FLOCH and MERLE, 1978; PICAUT *et al.*, 1978) show the alternation of the marine seasons can be envisaged mostly as the superposition of two annual and semi-annual waves. The works of WHITE (1977), MEYERS (1978a-b) and LUKAS (1981) in the Pacific, and of LUYTEN and ROEMICH (1982) in the Indian Ocean, tend to indicate the physical reality of these annual and semi-annual waves in tropical oceans. Even so these two waves could be simply due to the climatic influences of both hemispheres. But one must not forget these waves could be the result of an artifact of the mathematical Fourier decomposition of an irregular seasonal cycle.

The long cold season dominating the seasonal cycle features an upwelling, which springs up along the equator and the north and south coasts of the Gulf of Guinea. This upwelling is directly linked to the displacement of the thermocline (MORLIÈRE and RÉBERT, 1972; HOUGHTON, 1976; MERLE, 1980a), but, as yet, neither the role of the local wind forcing (BERRIT, 1976; HOUGHTON, 1976; BAKUN, 1978), nor solar radiation (MERLE, 1980a), nor even the increase in vertical mixing at the equator (VOITURIEZ and HERBLAND, 1979 ; VOITURIEZ *et al.*, 1982) adequately accounts for the phenomenon. Along the northern coast, part of this upwelling could be induced by the intensification of the Guinea Current, either directly with the geostrophic adjustment elevating the thermocline (INGHAM, 1970; PHILANDER, 1979b) or indirectly via a dynamic effect on the Cap Three Points and the Cap Palmas in Ghana and Ivory Coast (MARCHAL and PICAUT, 1977). For a review of all these various mechanisms see PICAUT, (1983).

The Gulf of Guinea is characterized by a thermocline which is always close to the surface. The zonal thermocline slope in the entire equatorial Atlantic strip undergoes seasonal variations revealed by the swing of the slope about a pivot point lying at approximately 25-30° W (MERLE, 1980a). KATZ *et al.* (1977) and LASS *et al.* (1983) correlated the variations of the corresponding dynamic slope in the central and western equatorial Atlantic with the seasonal variations of zonal wind stress in the same region. It may then be that the seasonal cycle in the Gulf is in great part the result of an adjustment on the scale of the equatorial basin.

3.2. The theory of remote forcing

During the FINE (FGGE-INDEX-NORPAX-Equatorial) workshop held at the Scripps Institution of Oceanography in California between June 22 and August 12, 1977, a small group of French scientists presented the case of the Gulf of Guinea upwelling to American theoreticians. Subsequent debate based on the French data, the latest equatorial theories (MOORE and PHILANDER, 1977) and a recent theoretical explanation of El Niño (WYRTKI, 1975; McCREARY, 1976; HULBURT *et al.*, 1976) led to the hypothesis that this upwelling could be induced by an intensification of zonal wind in the western part of the equatorial Atlantic (MOORE *et al.*, 1978).

The theoretical context of this hypothesis was illustrated by two reduced gravity models in which easterly winds confined to the western part of the basin start blowing suddenly (O'BRIEN *et al.*, 1978; ADAMEC and O'BRIEN, 1978). A piling up of water occurs along the Brazilian coast creating a zonal pressure gradient which balances the wind stress in agreement with KATZ *et al.* (1977) and LASS *et al.* (1983). Eastward of the wind's influence area an equatorial upwelling occurs, propagating eastward along the equatorial wave guide in the form of an equatorial Kelvin wave. This wave upon arriving at the African coast is reflected as packets of Rossby waves propagating westward near the equator and as two coastal Kelvin waves propagating poleward. This entire set of waves spreads the upwelling signal, generated in the center of the equatorial Atlantic, throughout all of the Gulf of Guinea. We used this theoretical representation, based at the time on sparse physical evidence, as a guide for the gathering and processing of data with which to validate or invalidate this new hypothesis.

3.3. Propagation of the seasonal upwelling

In May 1977, J. M. VERSTRAETE set up, in Ivory Coast, new coastal stations of daily SST measurements. Six new stations were added to the nine already existing in Benin, Togo and Ghana. At the end of 1979, we had a set of almost three years of systematic measurements along 1 200 km of the northern coast of the Gulf of Guinea. As discussed earlier, the seasonal cycle established by these chronological series suffers from wide interference due to a set of higher frequency oscillations, some of which can propagate. The adoption of a low pass filter eliminated all oscillations of periods less than or equal to 45 days. A lagged correlation analysis based on the long cold season enabled us to expose the propagation of the northern summer's upwelling along the coasts of Ghana and Ivory Coast (PICAUT, 1983) (Fig. 7). A similar analysis confined to the short cold season comes up with the same result (ROY, 1981). Apart from Pointe-Noire there are no longer any coastal stations along the southern coast. By way of preprocessed data of historical origin collected by merchant ships, kindly sent by S. HASTENRATH, W. WOOSTER, and A. BAKUN, we managed to show that the monthly climatological averages of SST in a grid of 1° squares also revealed this propagation along the coastline of Ghana and Ivory Coast. The use of this historical information on an average year off the southern coast of the Gulf of Guinea led to the discovery of the propagation of the upwelling signal from the equator to at least 13° S (Fig. 8). But it was impossible to isolate any such coastal propagation from the equator to the Ghana border. Probably, the upwelling signal does not appear in a definite manner in the SST of the northeast corner of the Gulf, which is characterized by a relatively deep thermocline and an accumulation of fresh water (BERRIT, 1973). Nonetheless, a correlation analysis turned up a 20 day lag between the passage of the coastal upwelling signal at the equator and at the Ghana frontier. The lag is the time taken by a 0.6 m/s wave to follow the coasts of the northeast corner of the Gulf. This phase speed is of the same value as the speeds indicated in Figures 7 and 8.

It now becomes highly possible to figure that the equatorial upwelling signal spreads into two coastal signals running along the north and south coasts of the Gulf. Along the equator, it was impossible to find a definite propagation (PICAUT, 1983). This could be owing to the difficulty of SST to reflect the upwelling signal, particularly in an average year, and also to probable equatorial interference between east-going equatorial Kelvin waves and west-going Rossby waves (CANE and SARACHIK, 1981).

Between 1957 and 1964, ORSTOM carried out 217 hydrological casts, over the continental shelf break, at a point 38 km south of Abidjan. A correlation analysis similar to the preceding ones indicated a vertical propagation of the upwelling signal (PICAUT, 1983), which occurs at a depth of 300 m, a month and a half before surfacing (Fig. 9). In no way can Ekman's theory explain such a depth and even less the progressive shift of phase up to the surface. We shall see that the superposition of waves

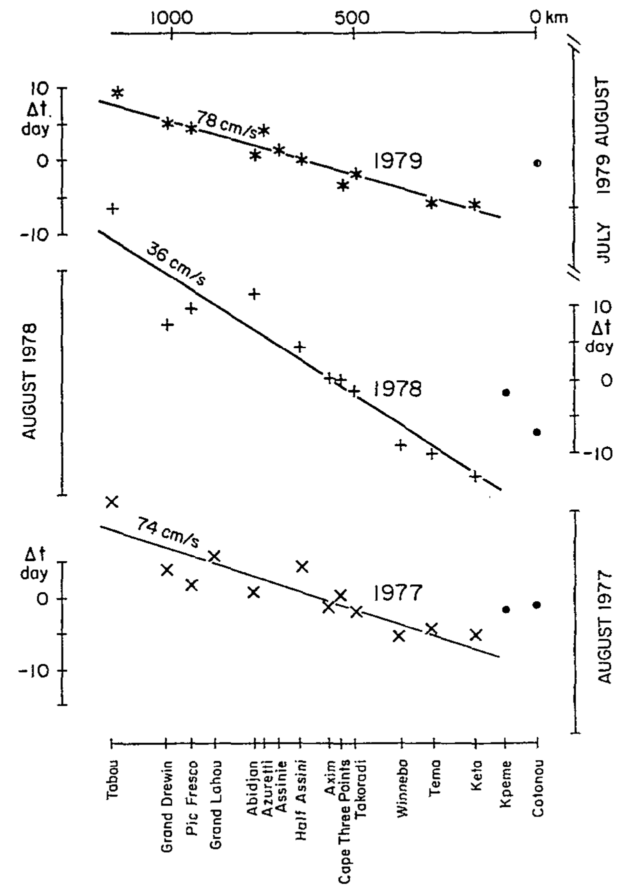

FIG. 7. — Propagation of the seasonal upwelling along the northern coast of the Gulf of Guinea deduced from daily sea surface temperature data collected at the coastal stations in 1977, 1978 and 1979 (from PICAUT, 1983)

Propagation de l'upwelling saisonnier, le long des côtes Nord du Golfe de Guinée, à partir des données journalières de température collectées aux stations côtières en 1977, 1978 et 1979 (d'après PICAUT, *1983)*

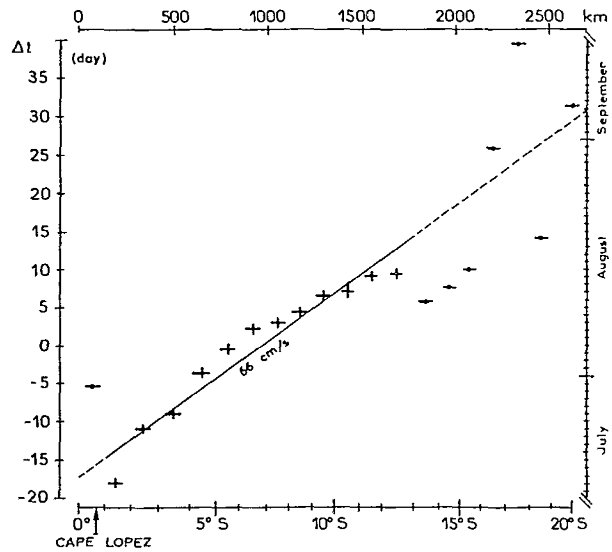

FIG. 8. — Propagation of the seasonal upwelling along the southern coast of the Gulf of Guinea deduced from merchant ship temperature observations averaged by month and 1° square areas (from PICAUT, 1983)

Propagation de l'upwelling saisonnier le long des côtes Sud du Golfe de Guinée à partir des données de température de navires marchands moyennées par mois et par carrés de 1° (d'après PICAUT, *1983)*

generated out of the Gulf of Guinea may account for such a phenomenon (McCREARY *et al.*, 1984).

3.4. Local and remote correlation between wind stress and SST

After this support of MOORE *et al*'s (1978) theory, we decided to analyze simultaneously wind stress and its possible repercussions on SST (SERVAIN *et al.*, 1982). Our research was greatly aided by S. Hastenrath, who sent us a repertory of winds and SST measured from merchant ships, averaged monthly on a grid of 5° squares for the 1911 to 1972 period.

Most of the previous studies were carried out on an average year, resulting in the smoothing out of phenomena particular to any given year. Moreover, on an average year, the dominant events, for wind and temperature, are annual. This voids all attempts to correlate such climatic means of temperatures and winds. By subtracting the mean seasonal cycle from both long time series of wind and SST, a significant correlation between the subsequent significant non-seasonal data should be considered a stronger indicator of the dynamic processes. We first showed that all the monthly thermal surface anomalies in the Gulf of Guinea are spatially coherent and that they differ widely from peripheral regions. We then demonstrated the close correlation between monthly anomalies of zonal wind stress in the western equatorial Atlantic and the monthly anomalies of SST in the Gulf with a lag of about a month (Fig. 10). This lag could correspond to the propagation of an equatorial Kelvin wave from the wind's influence area to the Gulf at a speed of about 1 m/s. On the other hand, local correlations between monthly anomalies in zonal and meridional wind stress and those of SST in the Gulf are of very low value (Fig. 10).

The last results are important in that they include the motor forcing (wind) and its remote oceanic response (SST), thus positively asserting MOORE *et al.*'s (1978) theory. But these analyses of correlation do not necessarily imply a causal relation. Such a rational relation can only appear in a detailed study

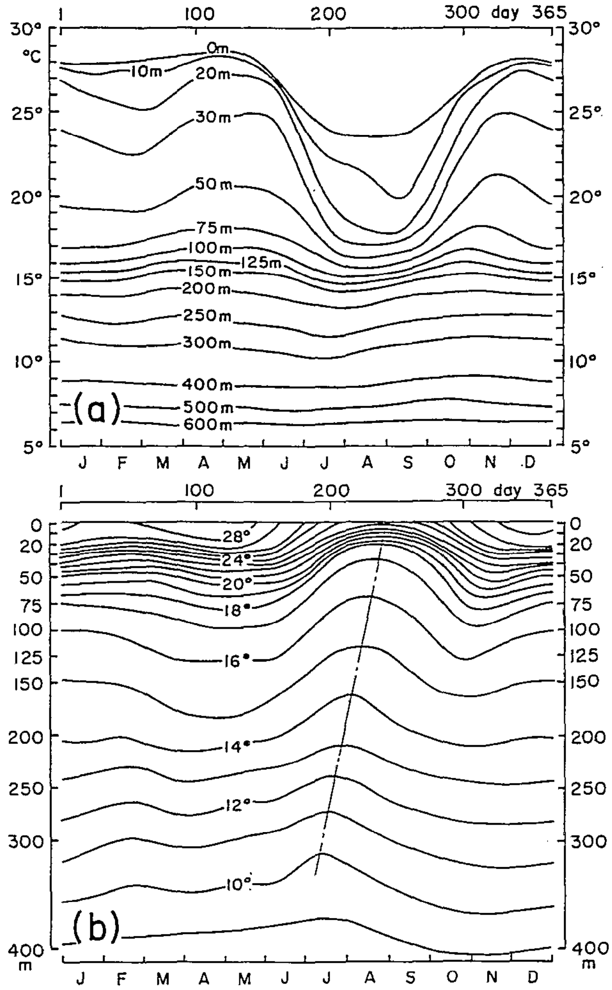

FIG. 9. — *(a)* Reconstituted seasonal cycle of temperature at standard depths deduced from hydrographical data collected 24 miles south off Abidjan. *(b)* Seasonal cycle of isotherm depths from the data of Figure 9a (from PICAUT, 1983)

(a) *Cycle saisonnier de température reconstitué aux profondeurs standards à partir des données de la station hydrologique 24 milles au sud d'Abidjan.* (b) *Cycle saisonnier des profondeurs d'isothermes à partir des données de la Figure 9a (d'après* PICAUT, *1983)*

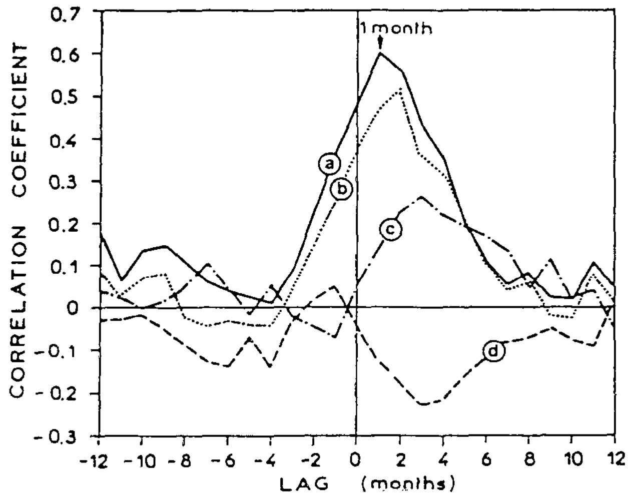

FIG. 10. — Correlation with time lag. Curve a: non-seasonal zonal wind stress in the western equatorial Atlantic with non-seasonal SST in the western part of the Gulf of Guinea. Curve b: non-seasonal zonal wind stress in the western equatorial Atlantic with non-seasonal SST in the northern part of the Gulf of Guinea. Curve c: non-seasonal zonal wind stress in the western part of the Gulf of Guinea with non-seasonal SST in the same area. Curve d: non-seasonal meridional wind stress in the western part of the Gulf of Guinea with non-seasonal SST in the same area (from SERVAIN *et al.*, 1982)

Corrélation avec décalage. Courbe a: anomalies de tension du vent zonal dans l'Ouest de l'Atlantique Équatorial avec les anomalies de température de surface dans la partie Ouest du Golfe de Guinée. Courbe b: anomalies de tension du vent zonal dans l'Ouest de l'Atlantique Équatorial avec les anomalies de température de surface dans la partie Nord du Golfe de Guinée. Courbe c: anomalies de tension du vent zonal dans la partie Ouest du Golfe de Guinée avec les anomalies de température de surface dans la même zone. Courbe d: anomalies de tension du vent médidien dans la partie Ouest du Golfe de Guinée avec les anomalies de température de surface dans la même zone (d'après SERVAIN *et al., 1982)*

of physical processes by a shrewd confrontation of model results and observations. The numerical simplified models of O'BRIEN *et al.* (1978) and ADAMEC and O'BRIEN (1978) were conceived as illustrations of MOORE *et al.*'s (1978) theory and did not intend to reproduce all the mechanisms of a true ocean. Additional simplified models were drawn up to emphasize other possible mechanisms, such as PHILANDER and PACANOSWSKI's (1981 b) model with regular southerly winds, and CANE and SARACHIK's (1981) model forced over the entire equatorial basin by periodical zonal winds. But in our case, the need to compare somewhat with observations made us use little more realistic models.

As mentioned in the introduction, there exists the inconvenience of models too sophisticated for use, so we resorted to an approach in two stages. In the first, BUSALACCHI and PICAUT (1983) used a model that reduced vertical resolution and integrated the seasonal wind as observed over an average year in a basin with a realistic coastline. In the second, MCCREARY *et al.* (1984) used a model whose coastline and winds were very simplified, but added up solutions vertically, giving a strong vertical resolution.

3.5. Reduced gravity model forced by mean seasonal winds (BUSALACCHI AND PICAUT, 1883)

This is a linear model also known as single mode model, or one-and-a-half layer model, as it comprises

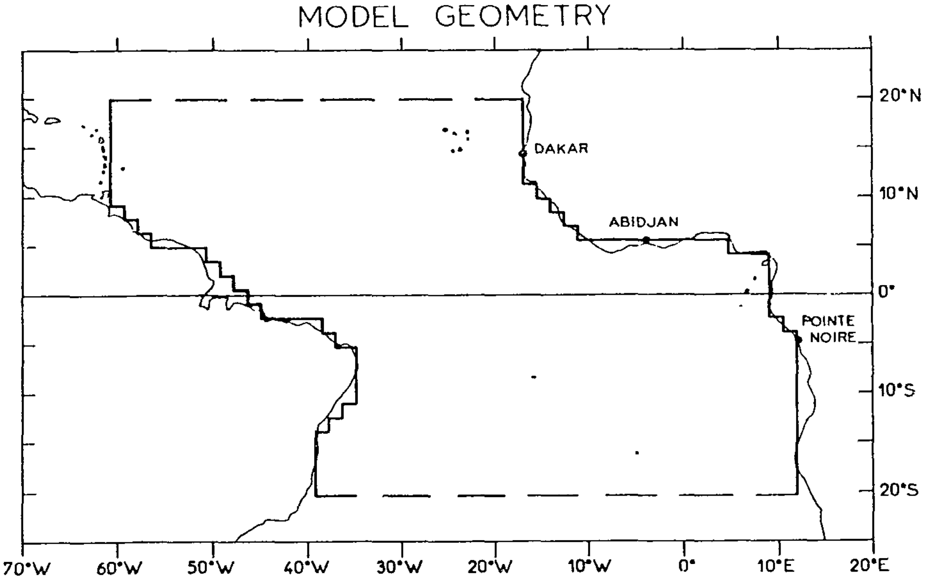

FIG. 11. — Comparison of the single baroclinic model geometry with the tropical Atlantic Ocean basin. The dashed line represents an open boundary. This model is forced by the mean seasonal winds deduced from 60 years of merchant ship observations (from BUSALACCHI and PICAUT, 1983)

Comparaison de la géométrie du modèle à mode unique avec le bassin Atlantique Tropical. Les lignes pointillées représentent des frontières ouvertes. Ce modèle est forcé par les vents saisonniers moyens déduits de 60 années d'observations par les navires marchands (d'après BUSALACCHI *et* PICAUT, *1983)*

only two layers, with the second being motionless. The wind acts horizontally by pushing the top layer and vertically by moving the pycnocline that separates the layers. This model is representative of a large area of the tropical Atlantic (Fig. 11). It is forced by winds recorded in HASTENRATH and LAMB's atlas (1977), which average merchant ship observations monthly on a 1° square grid for a period of 60 years.

According to SCHOPF and HARRISON (1983), a perturbation in the dynamic height responds linearly to the first baroclinic modes of the system, as opposed to the thermocline, which is more sensitive to higher modes and nonlinear terms. The results of other models (PHILANDER and PACANOWSKI, 1981a; McCREARY *et al.*, 1984) convinced us to use the reduced gravity of the second baroclinic mode calculated from observations in the equatorial Atlantic. Therefore, we compared the results of this model with the dynamic heights of an average year, obtained by MERLE and ARNAULT (1985). On the whole, the comparison is quite good, mainly concerning the mean and its annual variation. In particular, this model accurately duplicates the seasonal variations in the Gulf of Guinea (Fig. 12). One must note these results depend little on the speed of the second mode chosen (in an interval of 30 %) and are practically independent of horizontal viscosity. Moreover, these computations were made before MERLE and ARNAULT (1985), so in no way are they an adjustment to observations.

This rather accurate simulation enabled us to further the development of the equations inherent to the model and to rerun it while screening off different sectors of the wind. This way, we highlighted the mechanisms that determine the seasonal variations dominating the tropical Atlantic. In the northwest part of the model basin they feature a meridian pivoting about a line materializing the average position of the ITCZ (5° to 10° N). In the equatorial plane, there is a non-rigid east-west tilting movement of the model pycnocline around a point about 25°-30° W (MERLE, 1980a). The modelled seasonal response to the wind in an average year is a combination, depending on the geographical location, of locally forced responses, Kelvin waves, Rossby waves and multiple waves reflected by the coasts. On studying the mechanisms we saw that the pivoting north of the ITCZ's average position in the model is wholly due to the local forcing of the wind by way of Ekman pumping. The pivoting, in the opposite direction, south of this line is a combination of local and remote effects, i.e., wind stress curl and westward propagating Rossby waves. In agreement with KATZ *et al.* (1977) and LASS *et al.* (1983) we found that the zonal pressure

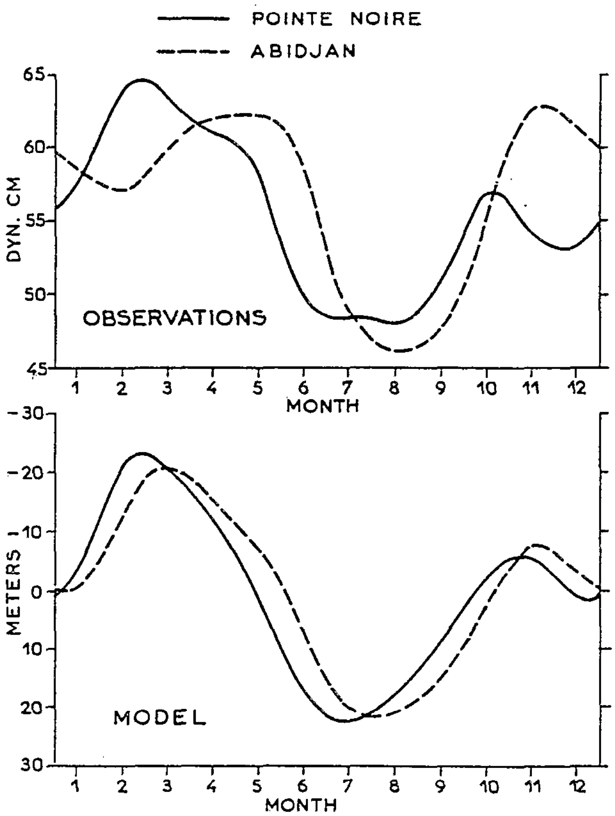

FIG. 12. — Comparison of dynamic height for 0/300 db with model pycnocline depth at Pointe-Noire and Abidjan. Negative values indicate that the pycnocline is deeper than the annual mean (from BUSALACCHI and PICAUT, 1983)

Comparaison des hauteurs dynamiques 0/300 db et de la profondeur de la pycnocline du modèle au large de Pointe Noire et d'Abidjan. Les valeurs négatives correspondent à une pycnocline plus profonde que la moyenne annuelle (d'après BUSALACCHI *et* PICAUT, *1983)*

gradient in the west of the equatorial strip is, during the whole year, balanced by the zonal stress of local wind. But in the equatorial strip of the Gulf of Guinea, there is no equilibrium between these two factors. Here, the model's response, for the most part, consists of a superposition of equatorial Kelvin waves generated by zonal equatorial wind west of the Gulf, and of Rossby waves, sprung from the reflection of the Kelvin waves on the African Coast. This reflection also induces a symmetrical response, which propagates poleward along the northern and southern coasts of the Gulf of Guinea (Fig. 13). Specific studies of the model under winds from various sectors revealed in detail the seasonal variations of the Gulf. West of 10° W the zonal equatorial wind accounts for almost the whole of the annual response of the Gulf's model. East of 10° W the annual zonal wind has side effects along the east-west oriented northern coast, canceled by the meridional wind's action along the north-south oriented coast. These results suggest the long cold season could be due, in good part, to forcing outside the Gulf. In the same region, half the pycnocline's semi-annual oscillation is in response to variations in the zonal component of the equatorial wind west of 10° W. The remainder of this oscillation is due to combined effects of zonal and meridional winds in the Gulf. This suggests the short cold season could be the result of the wind variability as much inside the Gulf as outside.

3.6. **Three dimensional model forced by simplified annual wind** (MCCREARY, PICAUT AND MOORE, 1984)

This model is an adaptation to Atlantic remote forcing of MCCREARY's (1981a-b, 1984) linear models, which studied the dynamics of equatorial and coastal undercurrents as well as deep equatorial jets. They are an extension of LIGHTHILL's (1969) non-viscous model by adding to it diffusion of heat and momentum in the deep ocean, which gives plausible results. The present model is forced by an oscillating wind confined to the equatorial zone west of 20° W (Fig. 14). The solutions are represented by the development of baroclinic modes in the system; in reality, adding up the first 15 modes is enough. The average vertical density profile used was calculated from historical hydrographic data of the tropical Atlantic's equatorial strip. Solution of a given mode is not found by integrating the equation of motion forward in time as is usually done but by hypothesizing, as in many tidal models, a reliance on time expressed by $e^{-i\sigma t}$, σ being the annual frequency.

Because of the absence of wind in the Gulf of Guinea, the response in this region is entirely due to the radiation of a set of equatorially trapped Kelvin waves, generated by the wind in the west. These waves superpose coherently so as to form a narrow beam of energy propagating rapidly eastward and slowly downward, following the σ/N slope, N being the Väisälä frequency for the level in question. The beam reflects off the African coast as a set of Rossby beams. This set, because it angles downwards at a steeper slope than the Kelvin wave beam, influences the sub-surface and deep structures of the Gulf. The more evident reflected beams correspond to the first horizontal equatorial Rossby mode and to a mode trapped along the northern coast (oriented east-west) very similar to a beam of coastal Kelvin waves. Other Rossby beams superpose generating coastal jets along the meridional coast (Fig. 15). This figure represents a vertical section of alongshore currents along the African coast from

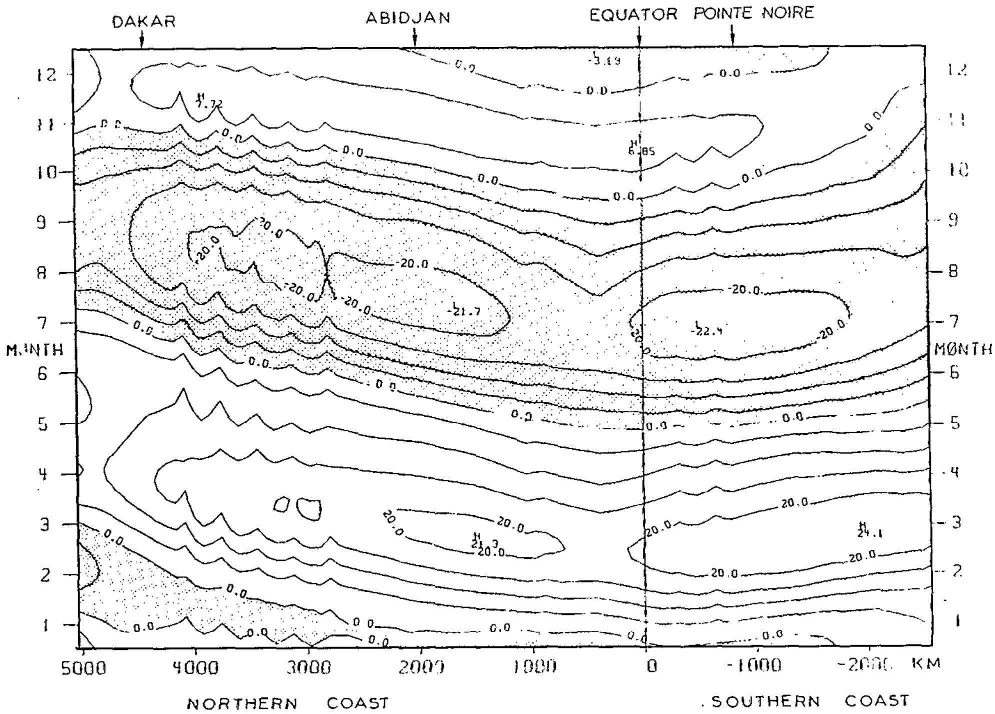

FIG. 13. — Seasonal pycnocline displacements (metres) along the northern and southern coasts of the Gulf of Guinea. Shaded regions indicate that the pycnocline is shallower than the annual mean (from BUSALACCHI and PICAUT, 1983)

Déplacement saisonnier de la pycnocline du modèle (en mètres) le long des côtes Nord et Sud du Golfe de Guinée. Les zones ombrées correspondent à une pycnocline moins profonde que la moyenne annuelle (d'après BUSALACCHI *et* PICAUT, *1983)*

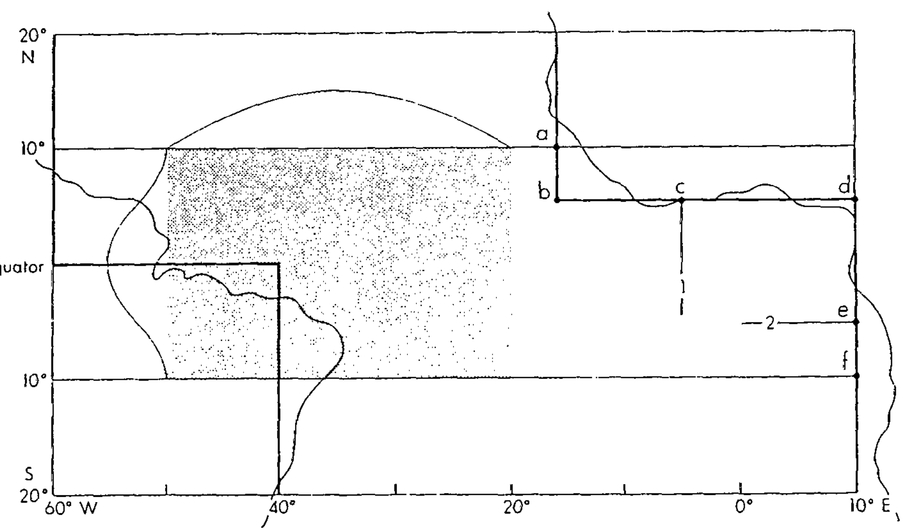

FIG. 14. — Comparison of the three dimensional model geometry with the tropical Atlantic basin. The thick lines indicate model continental boundaries and the wiggly lines the actual coastlines. Most solutions are found in a basin with open boundaries at ∓ 10°. The shaded region indicates the extent of the wind field, and the thin line its zonal and meridional profiles. The wind stress oscillates at the annual frequency and reaches a maximum of 0.5 dyn/cm² in the center of the wind patch (from MCCREARY *et al.*, 1984)

Comparaison de la géométrie du modèle à 3 dimensions avec le bassin Atlantique Tropical. Les lignes épaisses correspondent aux côtes du modèle et les lignes sinueuses aux côtes réelles. La plupart des solutions ont été calculées dans un bassin avec des frontières ouvertes à ∓ 10°. La région ombrée correspond à la zone d'action du vent et le trait fin autour schématise son profil zonal et méridien. La tension du vent oscille à la fréquence annuelle et atteint un maximum de 0,5 dyne/cm² au centre de cette zone (d'après MCCREARY *et al., 1984)*

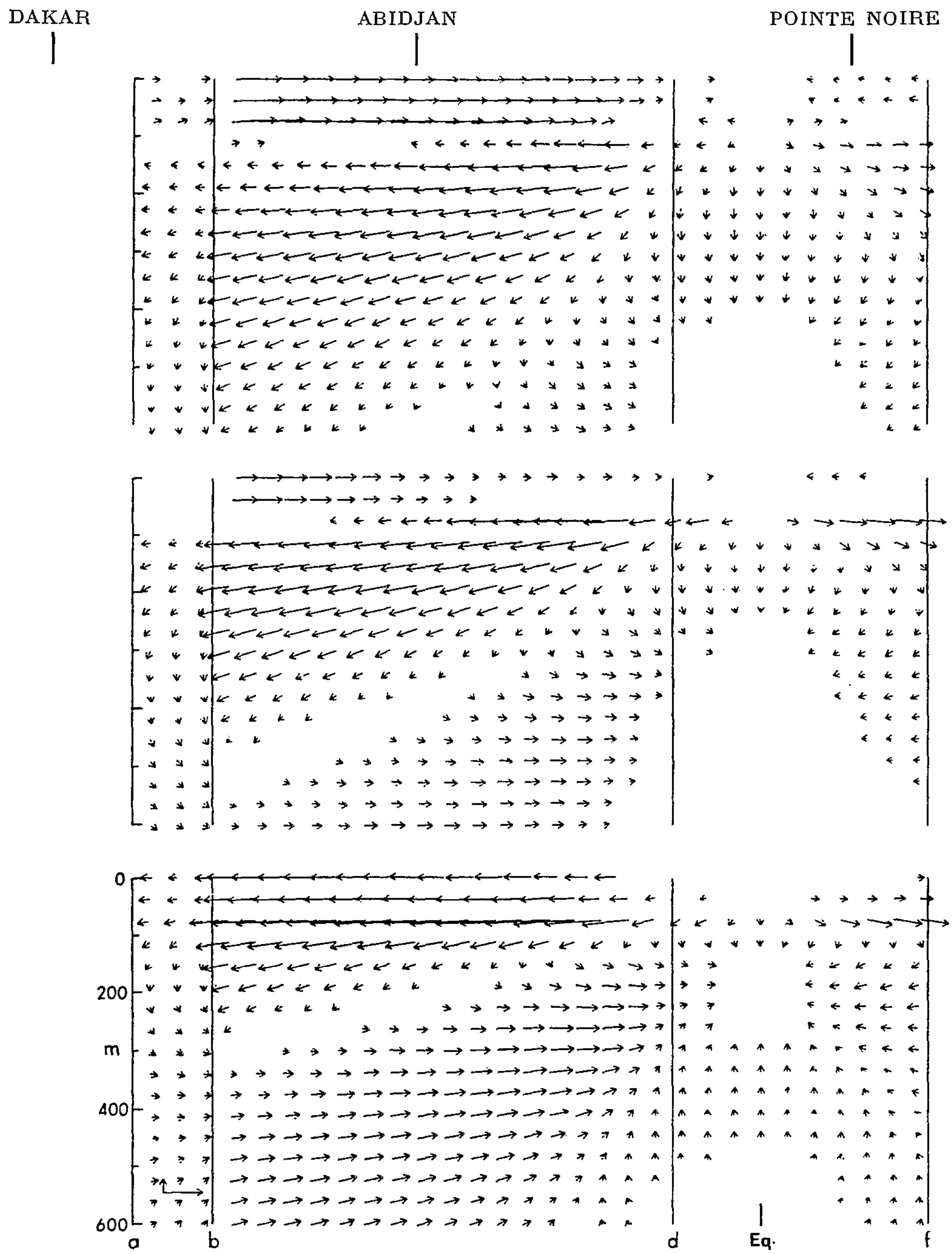

FIG. 15. — Vertical section of alongshore flow on the African coast from points a-f in Figure 14 for t = 6, 8 and 10 months in the upper, middle and lower panels, respectively. The calibration arrows in the lower panel are 0.001 cm/sec and 10 cm/sec in the vertical and horizontal directions (from McCREARY *et al.*, 1984)

Section verticale des courants le long des côtes Nord et Sud du Golfe de Guinée des points a-f de la figure 14 pour t = 6, 8 et 10 mois. Les échelles des courants situées dans la partie inférieure de la figure correspondent à 0,001 cm/s et 10 cm/s dans les directions verticale et horizontale (d'après McCREARY *et al., 1984)*

5° S to 10° N. The continuity of coastal currents and undercurrents right through the section demonstrates the currents are indeed caused by the reflection of an equatorial Kelvin beam. This figure also illustrates quite well the vertical propagation of the currents at a speed similar to the one we measured south of Abidjan. In almost the entire portion of this section, there also exists horizontal propagations of current and density fields, directed polewards at phase speeds of generally the same order as those observed *in situ*.

This model highlighted a basic observed difference in the coasts of the Gulf of Guinea. Along the top, east-west oriented coast, a coastal Kelvin beam traps the density and current structures along the coast, and because of Rossby waves along the north-south coast the same structures extend further offshore. Last of all, the model suggests the subsurface presence of an energy beam off Dakar, as a result of reflected equatorial waves excited from winds west of the Gulf of Guinea (Fig. 15).

3.7. Discussion and conclusion

Our observations suggest that the seasonal coastal upwelling of the Gulf of Guinea propagates poleward from the equator and vertically at least south of Abidjan. We also established a good correlation between nonseasonal variations of the zonal wind stress in the western equatorial Atlantic and nonseasonal SST variations in the Gulf of Guinea with a one month time lag, which is the time for an equatorial Kelvin wave to travel at approximately 1 m/s from the wind forcing zone to the Gulf. Both these results of observation are the major elements of MOORE *et al.*'s (1978) remote forcing theory, illustrated by O'BRIEN *et al.*'s (1978) and ADAMEC and O'BRIEN's (1978) models. Both models are so simplified that it is astonishing that our observations fit so well. Therefore, we shall conclude this chapter by discussing the results of recent models dealing with this remote forcing mechanism.

In O'BRIEN *et al.* (1978) and ADAMEC and O'BRIEN (1978) the zonal wind, confined to the western equatorial Atlantic, starts suddenly. The wind generates a front of equatorial Kelvin waves whose propagation appears clearly, as do those of ensuing reflected Rossby and Kelvin coastal waves. The response phase in the Gulf appears directly linked to the time the wind suddenly increased and to the speed of all these waves. Cane and Sarachik (1981), on the other hand, studied the linear response of a single baroclinic mode to periodic x-independant zonal wind forcing, in a basin defined by two simple north-south coasts. In their model, the periodic response is a complex superposition of Rossby waves, equatorial Kelvin waves and Rossby waves resulting from reflected Kelvin waves on the eastern boundary. Therefore, it appears impossible to detect equatorial Kelvin waves. Furthermore, at the annual frequency, coastal Kelvin waves can only exist above the critical latitude, which lies about 50° for the first baroclinic mode, and 5° for the tenth. There is no straightforward relation between forcing and its response in the Gulf of Guinea. BUSALACCHI and PICAUT's (1983) linear model, though similar to the previous one, used realistic coasts and winds, and has an equatorial solution much nearer to periodic forcing than impulsive forcing. In it, we were able to find a coastal poleward propagation in the Gulf (Fig. 13) and support for the idea that in this area the annual response is mainly the result of remote forcing. The propagation along the north-south coast is probably due to the uses of horizontal viscosity and harmonics of the annual wind stress frequency.

The linear three-dimensional model of MCCREARY *et al.* (1984), forced by an annual wind west of 20° W, simulates the vertical propagation observed south of Abidjan. The use of many baroclinic modes allows the energy to slope slowly downwards. This way the equatorial Kelvin beams and the reflected Rossby energy beams do not interfere completely, as they do in previous models. Thus, we find again the equatorial and coastal trapping enabling the visualization of Kelvin waves. Another explanation of equatorial and coastal waves evidence in a three-dimensional model is the damping of Rossby waves in the surface layers by nonlinear terms (PHILANDER and PACANOWSKI, 1981 a). These authors also find that when wind of an almost annual period is confined to the center of the basin, Kelvin waves east of this area appear and the response in the region, as in MCCREARY *et al.*'s (1984) model, is directly linked to this eastward propagating wave. As opposed to single mode models, in three-dimensional models it appears that there are no fundamental differences between remote periodic forcing and remote impulsive forcing.

One must keep in mind that the use of mean winds over an average year smooths very much the individual events of each year. SERVAIN *et al.*'s (1982) analysis of historical wind data and GARZOLI *et al.*'s (1982) direct wind measurements from St. Paul and St. Peter rocks near the equator at 29° W tend to show that the increase of trade winds west of the Gulf of Guinea is often of impulsive type. An interannual calculation similar to BUSALACCHI and O'BRIEN's (1981) is presently done to understand the differences between the mean seasonal cycle and the seasonal signal of individual years (PICAUT *et al.*, 1984).

All this research shows that a large part of seasonal variation in the Gulf of Guinea is due to the effect of zonal winds west of the Gulf. The first model gave indications of the importance in the response of spatial distribution and wind frequency. The second detailed the linking mechanism between remote forcing and its response in the Gulf. The two models are complementary despite the fact that in one model the energy can sink downwards, but not in the other. According to McCreary *et al.* (1984), the Gulf of Guinea's subsurface is mainly solicited by the first horizontal mode of reflected Rossby beam. As this beam is no deeper than 300 m in the Gulf, the comparison in the same region of the model's pycnocline of Busalacchi and Picaut (1983) with the dynamic heights 0/300 db is not at all incompatible. Further west the response seems mainly local and the Rossby beams can disappear downwards and/or be damped by nonlinear terms.

But all this work, obviously, is too incomplete to entirely account for all aspects of seasonal variations in the Gulf of Guinea. For instance the important changes of the Guinea Current between 2° and 4° N are ill explained by either model. According to Philander (1979b) and Anderson (1979) they could be caused by the influence of meridional winds in the Gulf. Our models are also devoid of advection, ocean topography, thermohaline and thermodynamic effects, and they do not allow the ocean to generate any SST variations. Unfortunately, only the numerous measurements of SST can, for the time being, supply us precise information on the seasonal and interannual ocean variations.

4. GENERAL CONCLUSION

This paper reported the main results of a series of inquiries, thereby shedding some light on thermal variations in the Gulf of Guinea. In the absence of a finer study, only the description of internal tides off Abidjan could be put forward, and Park's (1979) attempts to modelize them do not allow to conclude positively on any generation or propagation mode. But the 14.7 day period oscillation, influencing at least all the northern coast of the Gulf of Guinea, was studied in more detail. Although we now have some good ideas of its internal structure and its propagation mode, we are largely ignorant of its generation mode. One can imagine it being forced by a nonlinear interaction between both barotropic waves M_2 and S_2. A similar wide oscillation (1° to 2° SST amplitude) was uncovered along the Gulf's coast. It seems forced by an atmospheric oscillation of a 40-50 day period and is probably stationary. Further offshore the Equatorial Undercurrent meanders and the deep waves studied by Weisberg *et al.* (1979) emphasize the extent of medium-scale frequency oscillation in the whole of the Gulf of Guinea.

In the field of seasonal and interannual variations, we concentrated mainly on an original mechanism involving the zonal wind west of our zone of interest. At the beginning, a few vague observations and very theoretical ideas led us to hypothesize a process called Moore *et al.*'s (1978) remote forcing. Confrontation with direct and historical observations corroborated the prime elements of this simplified theory: (a) correlation between between SST and western surface winds, and (b) coastal upwelling poleward propagations. The details of this remote forcing mechanism were yielded by the implementing of two elaborate models, whose results were compared with observations. This work, resulting from a close collaboration between theoreticians and observationalists, enabled a better comprehension of the physics of the process which probably accounts for half or more of the seasonal and interannual variations in the Gulf of Guinea.

The great energy associated with medium frequency waves points to a possible generation of mean currents by these oscillations. Along the coast, these waves could induce large variations in seasonal upwelling (Houghton, 1976). They are probably at the root of important front movements, where tuna fish are found in high numbers (Stretta, 1977). Closer scrutiny of these medium frequency waves should logically elucidate the coastal dynamics and, at the same time, draw the boundary conditions of sophisticated oceanic models.

As for low frequency band, we already mentioned the difficulty of observing corresponding equatorial waves. Although the waves' reflections on ocean boundaries do not seem to be altered by a realistic continental shelf (Suginohara, 1981), their reflections on the bottom are still unsolved, as is the dissipation of all waves, which is fundamental for the notion of equatorial ocean memory.

Other key points are knowledge of the mechanism of energy transfer from the atmosphere to the ocean and knowledge of the quantity of this energy that crosses the thermocline (Philander, 1978a) and thereby generates deep equatorial jets (McCreary, 1984). The remainder of this energy is spent in the exchanges between both sides of the equatorial basin, and the part played by the three equatorial countercurrents is quite unknown in this exchange. Finally, the ocean reaction on the atmosphere, an important element in climatology, is the main goal of extensive future studies, but it presupposes a better collaboration between meteorologists and oceanographers.

More sophisticated models using the nonlinear and thermodynamic terms should solve some of these problems. But only specific and repeated measurements coupled, above all, to an even closer cooperation between theoreticians and observationalists can let us hope to further this line of research. In the tropical Atlantic the SEQUAL (Seasonal Response of the Equatorial Atlantic) and FOCAL (French Ocean and Climate in Equatorial Atlantic) experiments should clarify some of these aspects, and, if these experiments are concentrated on seasonal variations, medium frequency studies could develop thanks to equatorial moorings and inverted echo-sounders measurements. The Pacific Ocean is quite known, thanks to EPOCS (Equatorial Pacific Ocean Climate Studies), PEQUOD (Pacific Equatorial Ocean Dynamics) and the constant efforts bearing on El Niño and its associated Southern Oscillation. These types of experiments will continue under the TOGA (Tropical Ocean Global Atmosphere) program.

Even if highly sophisticated techniques such as satellite measurements yield valuable information on SST and, before the decade's end, on wind stress, we should not, in the near future, neglect simple measurements, easily collected and interpreted. If the picture of a good 20 people strung along the African coast, armed with one bucket and one thermometer, seems funny — let us remember that this paper, however modest, is largely based on such daily measurements.

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