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Foreword

"Time series of ocean measurements" was instituted by the Intergovernmental Oceanographic Commission (IOC) in 1983 in response to the need expressed by the research community to demonstrate the importance and usefulness of time series data to the understanding of oceanic and atmospheric processes. The historical events, such as the Tokyo Time Series Meeting in 1981, and the decisions which have contributed to the promotion of time series of ocean measurements, are outlined in Volume 1 of the series (IOC Technical Series No. 24, Unesco, 1983).

The primary purpose of this emphasis on time series is to support the World Climate Research Programme (WCRP) and to encourage the creation of data sets necessary for climate prediction. The WCRP entered a new phase in January 1985 when the first large-scale experiment with an ocean component - the study of the Interannual variability of the Tropical Oceans and Global Atmosphere (TOGA) - began.

The observational strategy of TOGA is to measure, for a ten-year period, the month-to-month variability of the temperature field and currents in the upper layer of the Tropical oceans in the latitude band 20°N to 20°S. The second large-scale WCRP endeavour, the World Ocean Circulation Experiment (WOCE), will begin later in the decade when oceanographic satellite systems, including at least one altimetric mission, are launched. The observational strategy for WOCE includes a global suite of in-situ observations for an initial five-year period including tide gauges, hydrography from research ships, expendable bathythermographs from ships of opportunity and drifting buoys. Several of the on-going time series projects presented in this volume address the observational requirements of TOGA and WOCE and are assisting scientists in establishing the criteria for the TOGA and WOCE observational strategies. These projects also have the potential of extending TOGA and WOCE, as the representativeness of the discrete ten and five-year experimental periods will be checked against earlier and follow-on data.

The time series volumes are prepared by the Joint IOC/SCOR (Scientific Committee on Oceanic Research) Committee on Climatic Changes and the Ocean (CCCO). This volume was edited for CCCO by Arthur G. Alexiou, a NOAA Consultant to the IOC.

The ideas and opinions expressed herein are those of the authors and do not necessarily represent the views of Unesco.

Finally, should you be interested in having an article published in this annual review, you are invited to submit an abstract to the Secretary, Intergovernmental Oceanographic Commission, Unesco, 7 place de Fontenoy, 75700 Paris, France.

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1. Climatically Significant Physical Parameters of the Ocean

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Introduction

Over the past decade, considerable progress has been achieved in understanding the complicated interdependence and interaction of various elements in the ocean-atmosphere system on a variety of scales. Still our knowledge is not sufficient to explain properly, not to say - forecast, the behaviour of the global climatic system. It is clear, however, that long-term systematic physical measurements in the ocean are esential as a substantial part of the future data base for relevant climatological studies. Various measurements of this kind have been made in the ocean on a continuous basis for a number of decades already. Experience gained from the analyses of the available data series and a critical evaluation of the relative importance of physical parameters involved are both extremely important for the planning of any new ocean monitoring effort related to the World Climate Research Programme. An attempt at such an evaluation is undertaken in this paper with respect to the following physical characteristics of the ocean and their climatological significance:

1. Sea surface temperature
2. Sea surface salinity
3. Temperature and salinity properties of the water column and of subsurface water masses
4. Velocities and integrated transports of major currents
5. Sea level variability

The authors have attempted to combine in one review the essential information which is not always readily available, it being widely dispersed in a variety of national and international publications.

Summation

The views expressed in this review reflect the authors' present level of understanding of the ocean and of its role in the climate system of the Earth. It is quite clear that further, and probably much better, opportunities to determine significant changes in the ocean climate will become available as a result of future research. New questions will arise and will be answered while various hypotheses will be tested through modelling and observations. The authors sincerely hope that this review may provide useful stimulation to those interested in building an efficient future system of ocean climate monitoring.

The Climatological Significance of Long Time-Series Measurements in the Ocean

It may be stated without exaggeration that the tasks that should be undertaken within a World Climate Programme (WCP) (18, 112) can only be defined now. This is because we have just reached the stage where we have the means to conduct climatological analyses of really long time series of physical measurements in the ocean, carried out over periods of as much as seventy to eighty years. Any serious attempt to define global climatological processes must involve research on the climate of the ocean and its variability as well as the effect of this variability on the climate of the entire planet.

We are now in a position to evaluate the results of the analyses of available long time-series measurements of the sea surface temperature (SST), the vertical distribution of salinity, sea level, current velocity and integrated transport, and other physical parameters of the ocean, and to consider the climatological significance of those results. We must also determine whether these series reveal any noticeable tendencies towards change in the climate. It is by no means possible to make such determinations unequivocally in every case. The high cost of obtaining long, continuous data series has repeatedly forced scientists to decide which series should be continued or discontinued, and whether to begin monitoring other parameters (or the same parameters in other areas) which might provide more substantial climatic information or prove less expensive (19). The general outlook for the development of physical oceanography up to the year 2000 indicates that long-term monitoring (with adequate means) of the physical parameters of the ocean considered important in understanding the variability of the climate will be conducted on a considerably larger scale (9). This therefore seems a useful stage at which to review the results of long time-series measurements of physical parameters in the ocean and to analyse their climatological significance. During this analysis we will use the definition of climate and the concept of the climatic system and its components given in (25).

It is important to be clear from the outset what we understand by 'climatically significant parameters' and what criteria we can use to assess their climatological significance. Above all, it should again be emphasized that we are interested less in the quasi-steady, long-term climatic background (the general pattern of which is already known) than in trends towards change in this background over periods of time of the order of several decades. Such changes may appear over broad regions of the climatic system or on a local scale (3). In theory, measurements of the entire set of physical parameters at any point in the world ocean should contain information about trends in the long-term variability of ocean processes. However, it is not clear how long such measurements should be made in order to identify trends. Observations of some parameters have been conducted for a very long time. It is, therefore, important to determine which of these actually reveal long-term alterations in the climatic system, and in which areas of the ocean.

At the same time as we accumulate new knowledge, our understanding of the physics of the ocean is constantly being extended and improved. The modern concepts of general oceanic circulation, the processes involved in its variability, the process of mixing and transformation of 'water masses', and the persistence of a quasi-steady pycnocline (10, 12) provide us with a rationale for the selection of a series of new measurements or analyses which could prove interesting and important for the study of climatic variability based on long-term monitoring.

In general, the task involves the selection of a specific measurement or alternate method for the statistical processing of available measurements of other parameters which would provide optimal identification (in terms of the effort involved and the signal-to-noise ratio obtained) of the climatic trends in which we are interested. We refer to such parameters as being climatically significant.

For example, some parameters have short-period and small-scale variations in amplitude which are considerably greater than the probable climatic trend over decades. According to data for the Northern Atlantic and the Arabian Sea, (67, 68), the climatic trend in the mean values of SST over the last fifty to seventy years is of the order of +1.0 to 1,5°C

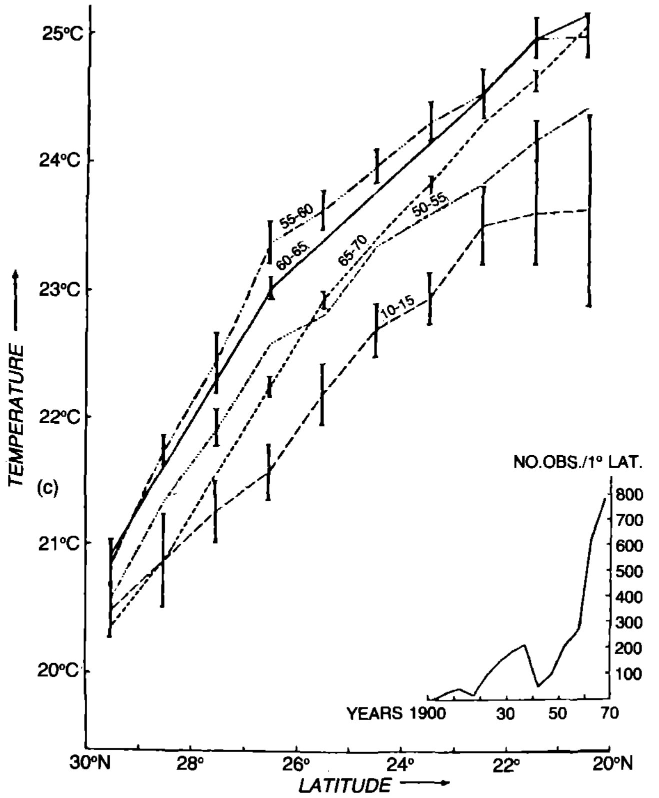

Figure 1a. *Variations of the sea surface temperature in Marsden Square 78 (20°-30° Lat. N., 50°-60° Long. W.) for 5 of the 6-year periods and the mean number of observations per 1° latitude strip function of the 6-year period after (67).*

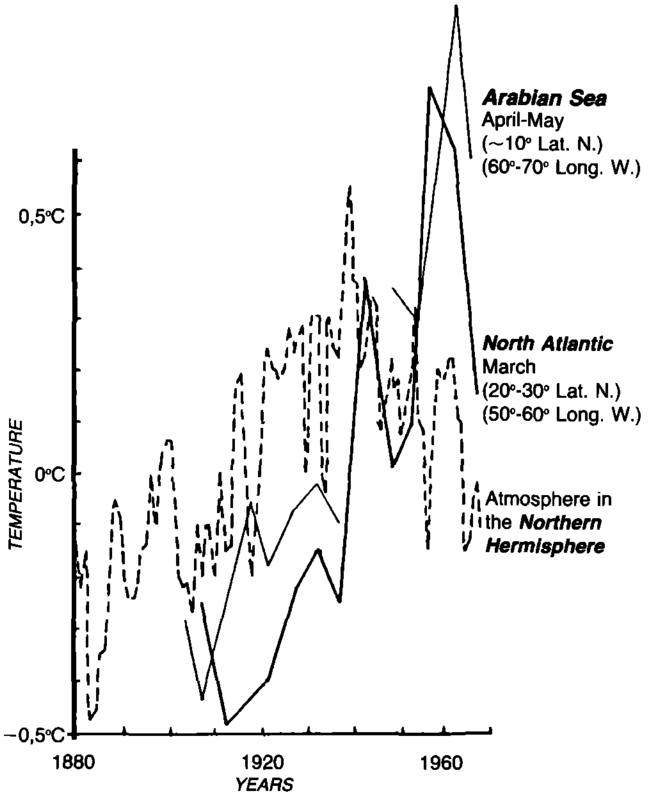

Figure 1b. *Mean sea-surface temperature anomalies in the Arabian sea, in the North Atlantic Ocean and air temperature anomalies in the Northern Hemisphere after (68) and (53).*

(Fig. 1). At the same time, local values for SST in the same regions may be subject to a daily oscillation of several degrees centigrade and seasonal variations of 10 to 15°C, while interannual variations in local average annual values may reach 1 to 2°C. It follows that local unaveraged values for SST would not provide the required climatic information in a clear form, even if a hundred-year series of such local measurements were available for analysis. But average annual values for SST, from which seasonal and daily cycles have been removed, and which have been averaged for the selected ocean areas to exclude local variability, can be used more easily to identify the climatic trend so long as the length of the series permits a reasonable smoothing out of noise and the detection of climatically important interannual variations. The climatic trend may also be identified by comparing average monthly or average seasonal values for SST for the same month (or season) over a sufficient number of years (66) (Cf. Fig. 1). It is quite clear that the gathering of initial data on SST must be carried out on a very regular basis (in time and space) in order to obtain average annual or monthly values of SST for the specific water areas selected for the purpose of the study of climatic variability. In general, the time-series measurements of any physical parameter of the ocean over many years, averaged or selected to filter out the high frequency components of variation and exclude local variability, constitute data sources for the optimal evaluation of long-term trends. All such measurements are, therefore, climatically significant.

On the basis of already accumulated SST data, it may be assumed that some water areas (where seasonal variability is low and the local interaction with the atmosphere does not completely determine the daily synoptic and interannual variability of SST) may be more representative than others for the purpose of identifying climatic trends. Such ocean areas may include areas of "climatic upwelling" caused by the general circulation of the waters of the ocean in tropical and subtropical latitudes (outside of a narrow coastal stretch 20 to 30 miles wide where local intensive upwelling is largely connected with local winds which, because of their direction, contribute to the upwelling). It is only possible to establish the optimal boundaries of such areas on the basis of careful research which also necessitates lengthy series of observations. The same line of reasoning also leads to the conclusion that the physical nature of other ocean parameters enables them naturally to integrate or smooth over many short-term and small-scale effects. One such example is the limit of the maximum dispersion of ice in the ocean. Another is the integrated transport of the main branches of the general circulation. The velocities and integrated transports of major ocean currents (the Gulf Stream, Kuroshio etc...) are practically insensitive to local (10 to 100 km radius), short-term (5 to 10 days) anomalies in the energy exchange between the ocean and the atmosphere, whereas SST is very sensitive to such anomalies. The sea level of the ocean, which varies with current velocity through the geostrophic relation, may be even less sensitive to local anomalies in energy exchange (with the exception of anomalies in atmospheric pressure) than the actual currents (151). Thus, recordings of the ocean level at strategic points, where variations in the level reflect the intensity of separate branches of general oceanic circulation, may be more directly revealing about profound climatological trends than the records of SST. In this connection, it may be pointed out that sea-level differences between judiciously selected pairs of level-measurement stations may be much more climatologically significant than the levels at any single point.

Neither can the possibility be ruled out that the mean temperature or salinity anomalies of any extremely conservative water mass, insulated from direct contact with the atmosphere, may be important climatologically. The physical mechanism of such anomalies may remain unclear until we are thoroughly familiar with processes leading to the formation of such conservative water masses. While on the subject of anomalies, it should be pointed out that some of them which subsist for several months or years may be manifestations or effects of various long-term climatic changes (24) and, thus, may contain important climatic information. On the other hand, the relatively short-term anomalous development of certain physical processes close to the surface of the ocean may have important climatic consequences, resulting in changes in the average conditions of deep waters in the following decades. Thus, according to the observations of the vessel "PANULIRUS" near the Bermudas, the temperature-salinity (T-S) anomaly in the sub-tropical mode waters of the Northern Atlantic ("18° water") formed at the end of the winter of 1964 lasted for 8 to 9 years (96). The intensification of the processes of formation of "18° water" in the particularly severe winter of 1976-1977 also produced a sharp displacement of the normally conservative T-S properties (96).

The examples considered above demonstrate what is meant by "climatically meaningful parameters". Their identification depends on specific features in each particular instance.

In turn, the climatic trends which interest us may be different in kind and significance. If only the climate of the ocean is involved, then the climatic trend or variation in the mean values of SST (for any given water area) may be an entirely adequate index. But if we are studying the effect of variability of the ocean climate on the climate of the continents or of the entire planet, then the integral of the heat content of the active layer of the ocean averaged as required over time and space would be more suitable for the purpose of studying changes in the climate than would SST. In this context, the variability in flow rates of the major branches of general oceanic circulation is more informative than the variation in current velocity near the sea surface. It is possible that global numerical models of the climate incorporating the variability of climatic conditions in the ocean in some form or other (as was done in the "Sections" programme (18,87), for example, will reveal which other integral characteristics of the thermodynamic state of the ocean are the determining factors or which may contain information relative to changes in the global climate.

In concluding this introduction, it should be noted that many attempts at climatological analysis of long (30- to 50-year) time-series of oceanographic measurements were made 20 to 30 years ago. The links between climatic variability in the ocean and the atmosphere were quite widely researched. To a great extent, the new WCP Programme in this area started from zero and much past research was overlooked. Attention was redrawn to it recently by Kondrat'ev (18-20). One of the aims of the present review is to draw special attention to the most important oceanographic problems of climatological analysis identified in the work which has already been completed.

Oceanic Climate Monitoring: Lessons and Prospects

Some methodological aspects. Before proceeding to a discussion of the main climatically significant parameters, let us dwell for a moment on a few general questions about methods for evaluating long-term trends on the basis of time series of ocean measurements.

Many researchers have already tried to describe processes of the climatic system by analysing the variability of the physical parameters of the ocean. Their efforts have been mainly concerned with describing the features of the sea surface which lend themselves readily to observation, i.e., sea level, temperature, and salinity. Because of the paucity of data, long-term changes in these features were, in the main, examined locally, over small areas in isolation from other oceanic parameters and the climate system as a whole. Evaluations of the extent to which local trends reflect global climatic processes became possible as a result of major conclusions drawn from data obtained from vast areas of the ocean. One of the pioneers in this field of activity was Smed, whose analyses covered the years 1940-1960 (127, 128). Later, after having collected and analysed data for many years, Stommel and Fieux (67, 68), and Paltridge and Woodruff (107) identified general climatic trends with respect to a number of different ocean areas. Investigation of the interaction between long-term changes in the sea and atmosphere began with the works of Bjerknes (49, 50). The climatic significance of the parameters examined by Bjerknes and other authors of joint studies of the sea and atmosphere is determined, as they suggest, by the interaction of the basic components of the climatic system (sea-atmosphere-land).

The aforementioned studies as well as a number of others (15, 16, 21, 32, 33, 34, 57, 70, 74, 111, 118) covered the longest (over 70 years) series available. At the same time, other efforts were being made to identify climatic trends based on data for 40-50 and even 20-30 years (42, 46, 54, 58, 59, 75, 81, 82, 89, 102, 109, 110, 116, 125, 126, 134-136). The comparatively short duration of these series undermines the reliability of a great many estimations of trends and, what is more, makes it impossible to extrapolate the trends so identified. The scarcity of data for long time-measurements is most acutely felt in the analysis of the characteristics of the water column. In several instances (73, 91, 114, 125, 131, 146), long-time changes in the deep sea were determined from the results of measurements separated by decades.

An analysis of the results of past investigations shows that only in a very small number of cases was the identification of a trend and natural climatic variability (fluctuations relative to the trend) done with adequate scientific rigor. Most of the authors cited above, in their study of climatic trends using the longest time series, failed to consider the natural climatic variations which are important for a correct analysis. Only

Rossiter (118), Stommel and Fieux (67, 68) and Privalsky (32-34) made a thorough examination of the series they had at their disposal. Privalsky, for example, in order to separate the linear function of time (αt) from the series x_t $(t=1,\dots,n)$ of values of the hydrometeorological element x, used an optimum detecting linear filter (115). The trend was considered statistically significant if the value $\hat{\alpha}$ of the slope α exceeded in absolute value three times its mean square error $\sigma_\alpha = \left(\frac{12\ \sigma_r^2}{n^3}\right)^{1/2}$ where σ_r^2 is the variance of a series after exclusion of a trend. Thus, a definitive conclusion about the presence of a linear trend was drawn only after estimations of the mean background $\bar{x}_t$ had been made and a general description given of the variability of data, i.e., the variance: $\sigma_x^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2$ In that connection it should be noted that it is important to take into account natural climatic variability because trends of climatic change could become apparent through the variances. The more or less regular interannual fluctuations (like those of the El Nino type) and even seasonal fluctuations can exhibit long upward or downward trends. For instance, it is possible that changes in the time of the onset of anomalous events of one kind or another occur as a result of long-term rearrangements of cyclical processes.

It is quite clear that the climatic representativity of trends resulting from long time-series observations depends on the degree of their quantitative and qualitative homogeneity. Many studies (22, 23, 29, 46, 52, 74-77, 119 and others) noted that the original data were either unevenly distributed in time and space, or were obtained by measurement methods that changed from year to year. Therefore, available observation data have to be sorted and filtered to discover climatic trends.

It is no accident that one of the first steps of the organizers of the World Climate Research Programme (WCRP) was to convene a meeting on Time Series of Ocean Measurements in the Spring of 1981 (Tokyo, 11-15 May) (86). The meeting helped to unify and critically review all major international and national programmes for monitoring physical oceanic parameters. Anyone interested in detailed information on these programmes should acquaint himself with the papers presented at that meeting. The list of papers together with a brief description of their content and relevant recommendations, are given in the work mentioned above (86). We shall limit ourselves here to an enumeration of the principal parameters discussed and cite the sources of already existing long series of measurements, pointing out the main problems resulting from their analysis.

<u>Sea surface temperature (SST)</u>*. This parameter is convenient because it is easy to measure and has been measured more than any other parameter since the beginning of the century. Moreover, scientific, merchant, and military vessels have traditionally assisted in the measurement of this parameter. One of the major sources of long-term SST data in the North Atlantic and the seas around Europe is the Archive of the International Council for the Exploration of the Sea (ICES), which was founded in 1902 (see, for example, 58, 127). One of the shortcomings of available data is their irregular distribution in time and space, a fact which complicates the matter of averaging which is so essential for climatic analysis. What may be considered as other shortcomings are frequent errors in thermometer readings, errors of bucket measurements and intake recording systems, different measurement methods on different vessels and in different years, and calibration errors.

This is particularly true for information collected by ships of opportunity. It is precisely this information that comprises the basis of the known data sets of time-averaged and space-averaged water temperature values in the Pacific and Atlantic oceans (31, 36, 37, 69, 106, 127, 128, see also 54, 58, 67, 68, 70, 107) mentioned earlier. It is important to bear two things in mind in using such data. First, when space- and time-averaging is employed, an increase in the number of observations does not guarantee a finite increase in the accuracy of estimations of mean values, one reason being that there is always the chance of error connected with the finiteness of the field of averaging (22). Second, starting with the 1960s, the quality of large-scale SST observations continually deteriorated as a result of the increased number of vessels reporting intake water temperatures. The widespread application of this method leads to a

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* Recently there has been a noticeable tendency to apply the abbreviation SST only to temperature values strictly related to the physical surface of the sea, for example, to the values reconstituted from infra-red radiometry data from satellites or aircraft. We shall use this abbreviation in the broadest sense of the term for all temperature values obtained by whatever means to describe thermal conditions of the sea surface.

systematic overestimation of the temperature, thereby affecting the recorded long-term SST variations. A change in the proportionate number of vessels using bucket and intake measurements could in time lead to a systematic increase in mean SST values for the World Ocean of between 0.5 and 1.0°C (23, see also 44).

On the other hand, the volume of data being collected by research vessels is growing, and the techniques for measuring are inevitably improving. However, the improved techniques occasionally complicate the analysis of the climatic variability of the time series being collected. Thus, along with the change in methods and improvement in the quality of measurements of SST and salinity at weather station 'Papa' in the Pacific Ocean, there was a change in the statistical character of the series obtained, in particular a decrease in the variance (132).

In the evaluation of SST as a climatically significant parameter, it is important to remember that under different physical sea surface conditions, momentary local values of true SST can differ substantially (from 1 to 3°C) from water temperature values at the 1-3 m level (8). In some instances this presupposes the presence of a sharp vertical temperature gradient in the near-surface ocean layer which can lead to significant systematic errors when different groups of vessels engaged in SST measurements systematically take readings at different subsurface depths.

The climatic significance of SST is to be sought in timeand space-averaged measurements of initial observation data carried out on such a wide scale as to nullify most of the short-term effects. Moreover, we are inevitably moving toward the point where mean SST values are associated with changes in the heat content of the active oceanic layer. The latter is marked by considerable heat inertia and accumulates and smooths out small-scale and short-term effects.

To evaluate the scale on which averaging must be carried out, it is sensible, from the outset, to take advantage of the possibilities offered by already existing and frequently used data series. It is also important that in all extant works (43, 64, 97) the connection between SST fluctuations and changes in the heat content of the active oceanic layer* was examined with respect to already averaged data sets from which were excluded regular, mainly daily and seasonal, fluctuations. On the basis of methodological studies dating back to the end of the 1950s (121, 122 and others), it was recommended, in considering the factual density of hydrometeorological observations in the sea, that an effort be made to build up long-term monthly mean time series and a long-term space series averaged out over 1° x 1° to 10° x 10° squares. SST data have also been generalized in accordance with these recommendations (31, 36, 37, 52, 106, 128 and others). The enormous body of data thus built up represents an up-to-date array of the most detailed and continuous data on SST.

Let us now try to answer the question of the extent to which long-period fluctuations of mean monthly SST's are in line with changes in the heat content of the active oceanic layer. In his study, Bunker (54) asserts that short 20-25 year trends of values of mean monthly SST anomalies, averaged out over fairly large areas (Marsden squares measuring 10 degrees latitude by 10 degrees longitude) are in line with the trends of values of the amounts of heat absorbed by the ocean. Other studies (43, 64, 97) show that the most pronounced interannual anomalies in mean monthly oceanic temperature patterns are seen, for the most part, in the upper 100 metres. Measurements in the temperate latitudes of the North Pacific (145) show that anomalies near the surface are characterized by a higher degree of intermittence and variability than those observed at a depth of 100-250 m. On the basis of such data, Emery (64) showed that there was comparatively little correlation (0.38) between fluctuations in the heat content of the active oceanic layer (0-250 m) and SST anomalies. In his analysis of measurements carried out with the help of expendable bathythermographs dropped from aeroplanes, Barnett (43) also established that SST summer anomalies do not reflect more deep-seated anomalies in the heat content of the active oceanic layer. Continuing to carry out similar measurements and analysing them with the help of empirical orthogonal functions, Barnett (43) came to the conclusion that SST anomalies are mainly connected with the thermal state of the oceanic upper mixed layer. Merle's findings (97) also indicate substantial differences between anomalies in SST and those in the integrated heat content of the 0-300 m layer in the eastern Equatorial Atlantic. Tabata (133) cites some curious data collected over the period 1956-1978 at weather station 'Papa' in the North Pacific. He shows that in 1960 and 1974,

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* See also the later section on the heat content of the active oceanic layer.

in the region of station 'Papa', there were extremely sharp anomalies in water temperature --on both occasions positive-- at the 200-1000 m ocean depth. At the ocean surface, in the same region and for the same two years, no particularly strong anomalies were observed in water temperature. Thus, mean monthly SST data reflect climatic trends restricted to the thin upper layers of the ocean in regions where there is no strong, stable vertical motion.

Pursuing our discussion about establishing links between mean SST values and the heat content of the oceanic upper layer, let us consider mean annual averages. Mean annual SST values comprise the second major group of long-term observation data under study (33, 34, 49, 64 and others). Emery's findings (64) show that mean annual SST values in the area of weather station 'N' correlate much more closely with anomalies of the heat content of the 0-250 m layer than with mean monthly SST anomalies. In Emery's view (64), these findings indicate that interannual changes in the thermal capacity of the active oceanic layer are, to a considerable extent, determined by the interannual variability of slow vertical motion. In turn, interannual changes in the heat content of the 0-250 m layer form the basis for determining the year-to-year variability of mean annual SST values, from which regular seasonal motion is excluded (by means of averaging). Hence the conclusion that the year-to-year variability of mean monthly SST values is climatically less representative owing to the irregularities of seasonal oscillations which may have their own interannual trend.

It is possible to obtain mean annual SST values having still greater representativity for describing the climatic variability of extensive oceanic areas by averaging out data on large areas as, for example, the so-called Smed squares (in the Atlantic). Thus, Prival'sky (34) ascertained the presence of consistent SST linear trends in 4 out of the 5 Smed squares (37) he examined. Linear trend variance accounted for 1/5-1/6 of total series variance. The general conclusion that can be drawn from this analysis is that there has been an increase in temperature over the past century and that the increase has been most pronounced in the regions closest to the Arctic. If we take as a standard the average temperature for the whole observation period 1881-1970, it becomes clear that since 1925 (halfway through the observation period) there has been a 0.3-0.5^{o}C increase in temperature. It is interesting to note that the average zonal temperature of the air above the North Atlantic in the five-degree latitude zones whose northern limits extended to 55^{o}, 60^{o} and 65^{o} Lat. N. showed no significant climatic trend.

The absence of any direct connection between SST and atmospheric climatic changes may mean that the examined series are still too short to reveal such linkage. This was the conclusion reached by Fieux (66) after comparing SST trends in the western North Atlantic and in the Arabian Sea (67, 68) with long-term changes in the mean atmospheric temperature of the Northern Hemisphere for the period 1880-1970 (53) (Fig. 1). We would note in passing that the SST trend in Marsden square No. 78, bounded by 20^{o}-30^{o} Lat. N. and 50^{o}-60^{o} Long. W. (see 67, 68), for the period 1940-1970, differed considerably from the trend observed in adjoining Marsden squares Nos. 80 and 115 (15).

It is possible, however, that SST climatic variability is more consistent with long-term changes in the characteristics of atmospheric circulation. As early as 1962, Bjerknes (49) established quite clear-cut physical links between climatic patterns of changes in SST (for short and long periods) and the index of atmospheric circulation for the region of the North Atlantic between Iceland and the Azores (difference of atmospheric pressure Vestmannaeyjar-Ponta Delgada). At that time Bjerknes was already raising some vital questions for further study that had to do with the reasons for the duration and shift in the character of the established climatic trends while their interaction was maintained (see also 38, 40). Bjerknes' well-known hypothesis about self-sustained fluctuations in the ocean-atmoshere system every few years prompted Colebrook (57) to compare long time series of measurements of hydrometeorological characteristics. Referring to the works of other authors, he used data on the sea level at stations along the Florida coast as an index of changes in the speed and flow of the Gulf Stream, and data on the frequency of tropical cyclones (Fig. 2) as an indicator of long period fluctuations in the intensity of atmospheric circulation above the North Atlantic. He noted that the climatic patterns of atmospheric circulation, intensity of the Gulf Stream, and the SST of the northeastern North Atlantic are closely linked with one another (see also 88).

Pursuing his investigation of the interaction of sea and atmosphere, Bjerknes (51) linked the interannual fluctuations of

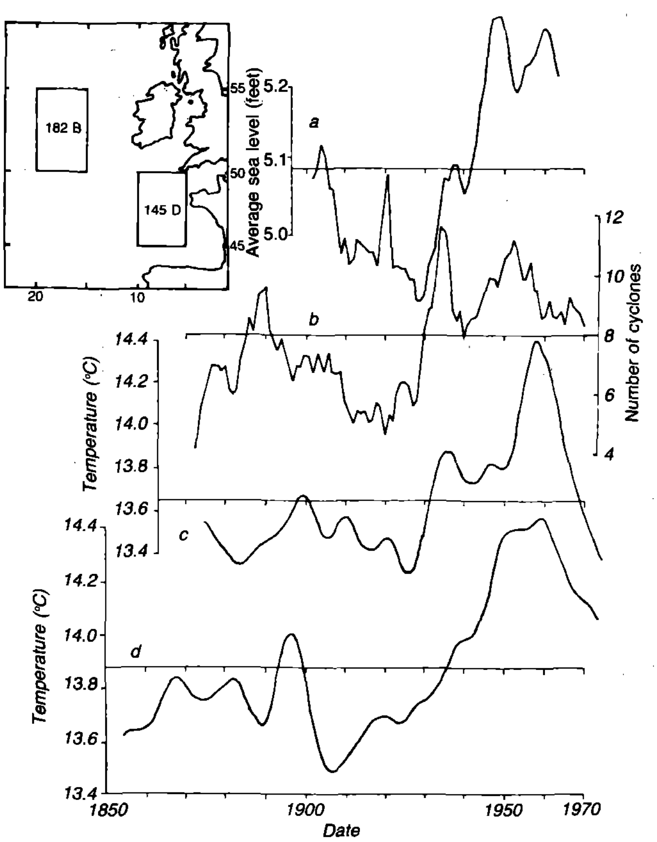

Figure 2

a. *After (57), 5-yr running mean of average sea level at stations along the coast of Florida.*

b. *7-yr running mean number of Atlantic tropical cyclones.*

c. *Smoothed variations of sea surface temperature for Marsden Square 182B (50-55°N, 15-20°W).*

d. *Smoothed variations of sea surface temperature for Marsden Square 145D (45-50°N, 5-10°W). The variables in c. and d. were both smoothed by the application of eigenvector filters which, in both instances, were approximately equivalent to 7-yr running means. Inset shows position of Marsden Squares 145D and 182B.*

the temperature regime of the equatorial Pacific across Walker's atmospheric gyre with equatorial atmospheric circulation over the Indian and Pacific oceans, and across the Hadley cells with the large-scale variability of atmospheric circulation in the medium and high latitudes of the Pacific and Atlantic oceans. There are also other working hypotheses that require full-scale verification. One of them, based on a whole series of serious studies (55, 62, 105) concludes that interannual variability of SST in the low latitudes and especially in the region of the Equator is one of the major factors governing interannual SST fluctuations in mid-latitudes, such as, for example, El Nino (104). The events connected with the anomalous increase in SST in the equatorial Pacific in 1982 fully confirmed this hypothesis (138, 139).

New prospects of understanding the mechanisms of long-term SST variability were opened by Hasselman's 'stochastic climate models' (77)*. These are based on the idea that climatic fluctuations can be viewed as the reaction of slowly changing components of the climatic system (ocean, cryosphere, land vegetation) to continuous short-period 'weather' effects of the atmosphere. The results of numerical modelling (4, 93) and of the experimental study of spectra and predictability of large-scale processes (41, 32, 33, 5) are very much in line with Hasselmann's theoretical ideas.

Frankignoul and Hasselmann (72), using a simple one-dimensional model of the upper, quasi-homogeneous oceanic layer, showed that SST anomalies lasting over a month could be considered as the integrated response of the oceanic upper layers to the cumulative effect of synoptic atmospheric processes.

The generation of a long-term SST anomaly by synoptic atmospheric action has been examined on the basis of full-scale observational data (27). Under conditions of a quasi-stationary (on the scale of several years) synoptic atmospheric influence on a particular area of the ocean, the magnitude of its mean monthly intensity fluctuates stochastically. Highly intensive atmospheric processes lasting one or two months can lead to the formation of important SST anomalies, such as the negative anomaly that occurred in the vicinity of weather station 'E' in the North Atlantic in the summer of 1959. While average wind stress was the same for the summer months of 1958 and 1959, its variation in the second half of June - first half of July 1959 exceeded its intensity for the same period in 1958 by 1.5-2.5 times. This reduced by 25-30% the influx of heat into the atmosphere through the sea surface and increased by 2-3 times the influx of cold waters into the upper quasi-homogeneous layer from below due to entrainment. As a result, towards the middle of July the difference in SST values between 1959 and 1958 amounted to -3.8°C, and the anomaly that had developed was observed until mid-October.

Short-period atmosphere-induced perturbations of the ocean play an important

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* In this case, the term 'climate' covers interannual variability and even shorter-term fluctuations of oceanic physical characteristics, an interpretation which is not quite correct.

role in the formation of SST anomalies in many oceanic areas (4, 26, 113). Therefore, climatic variations of the averaged over many years variance of SST anomalies can serve as indicators of trends in the intensity of synoptic processes in the atmosphere and, accordingly, characterize long-term changes in the energetics of the atmosphere. Thus, with due regard for the fact that the oceanic upper layer constitutes the natural integrator of the energy of many and varied synoptic atmospheric influences, climatic monitoring of SST anomalies must be supplemented by systematic observations of such atmospheric parameters as wind in the boundary layer or representative differences in atmospheric pressure at carefully selected locations.

Wholly new horizons are opening up for SST monitoring (including climatic monitoring) with the improvement of methods of remote measuring of oceanic physical parameters by means of Artificial Earth Satellites (AES) (20). Modern scanning infra-red (IR) radiometers and microwave radiometers used on satellites, in principle, possess the technical characteristics sufficient for this purpose (see, for example, 47, 48). However, there are still a number of difficulties to be overcome, beginning with the need for correct calculation of the absorption effect of the atmosphere, and including a number of specific problems relating to the transmission, reception, processing and reduction of information. A number of the more important aspects of this question are discussed in 7, 11, 20, 101. The approach to the aforementioned problems should essentially depend on the way in which future users plan to use the data. Planning for satellite monitoring systems should thus integrate all aspects of the problem: choice of orbit, equipment, processing methods, etc. Moreover, at the initial stage, it would obviously be more profitable (from the standpoint of expenditure and the lessons to be learned from experience) to develop monitoring systems, especially SST monitoring systems, under specific programmes of limited duration (5-7 years) such as the 'SECTIONS' programmes.

Sea surface salinity (SSS). Preliminary evaluations of the climatic importance of SSS data, processed and averaged in different ways, can be obtained from the study of the published results of the analysis of comparatively short (1-10 years) SSS series (80, 99, 120) and of the available 15-20-year series (58-61, 82, 89, 132, 133).

Publications on the results of climatic analysis of SSS series covering a period of several decades have not been found. However, the ICES Archives contain pertinent measurement data which, at one time, was even summarized in the form of atlases and charts (83, 84). It is not inconceivable that in the past the climatic importance of SSS data was underestimated. Today, however, with improved methods of SSS measurement and the regular recording of such measurements by boats in transit, and also as the physical causes for and scale of space-time SSS variability (13) become clearer, interest in the study of the climatic changes of this feature is sure to increase. This would also seem to be indicated by the close relationship between SSS and evaporation from the sea surface and also by the importance of advection factors in SSS distributions. The latter was very convincingly shown by Dickson and Lee (60).

The role of oceanic upper layer salinity in shaping the climate of the whole hydrosphere, including its thermal regime, is apparently of great importance. The high salinity of the surface waters of the Atlantic, especially in the subtropical belts, which is connected with the high evaporation caused by the relative proximity of the continental mass, sharply contrasts (2-4^o/oo difference) with the very low SSS values in the same latitudes of the Pacific ocean (especially in its northern part), the width of which exceeds the width of the Atlantic along the Equator by 4 times. As a result, the waters of the Pacific are considerably more stable in the vertical and their structure is appreciably different from the vertical structure of the waters of the Atlantic. The two oceans have a basically different climatic background as regards both salinity and temperature (Fig. 4).* The higher salinity in the North Atlantic as compared with the salinity in the northern part of the Pacific is, to a certain extent, sustained by the transport of water vapour into the atmosphere above Central America (142). A decrease in the transport of water vapour as a result of a drop in global atmospheric circulation could lead to a decrease in salinity and temperature and more intensive ice formation in the North Atlantic. In that connection Perry and Walker (29) note that the increase in salinity that occured in the North-Eastern Atlantic during the first decades of our century was indeed accompanied by a warming of the climate in the area of the North Atlantic and a decrease in the quantity of sea ice. SSS monitoring in the northern parts of the

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* Several important aspects of this question are considered in the next section on T-S characteristics.

Atlantic and Pacific could facilitate a study of the causes of the consistent climatic changes in these important areas of the World Ocean.

Without salinity data it is difficult to differentiate between long-term changes in the ocean caused by the advection of water by currents and those caused by local fluctuations of the thermal regime and atmospheric humidity. Concrete examples of the importance of combined examination of patterns of temperature and salinity near the surface of the sea are provided by Smed and his co-authors (129). One example, in particular, is concerned with SST and salinity changes in the North Atlantic during the period 1948-1977 (Fig. 3). Citing the work of Taylor and Stephens who analysed the data of weather ships, Smed and his co-authors reported that by comparing temperature and salinity changes with each other and with the estimates of precipitation and evaporation, they were able to explain these variations by the advection of low salinity waters from the Labrador and East Iceland currents.

In general, average sea water salinity is such that the temperature at the point of greatest density lies below the freezing points. Oceanic climatic conditions would be quite different if the situation was reversed, as is the case, for example, in fresh and brackish lakes.

It follows from the above that SST monitoring is especially important in areas where the convective overturn of the whole water column can be expected under winter conditions, along with the formation of deep waters which then spread along the bottom of basins. Temperature-salinity (T-S) characteristics of the deep waters that are formed in the process should be closely linked with SSS and SST in the area of formation at the moment immediately preceding the onset of convection. SSS monitoring is likewise important in areas where there is continual sinking of the waters as a result of salinization during evaporation with the formation of intermediate waters (for example, of subtropical origin).

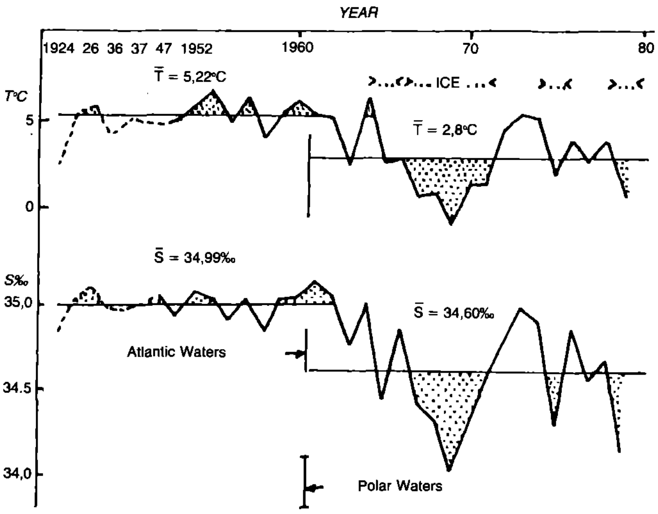

Figure 3. *Changes of SST and SSS in the North Atlantic (ICES area) from 1924 to 1980 according to Smed et al (129).*

<u>T-S characteristics of the water column</u>. T-S measurements of the abyssal water of the ocean have in the main been carried out by special research vessels. These measurements are, therefore, on the whole, more accurate than sea surface observation data*. The range of variations in abyssal water characteristics is, as a rule, rather small. The higher quality of deepwater measurements is very valuable for climatic analysis, but the frequency and number of measurements are also important. It is the irregularity of measurements and their often random distribution that continue to impede the progress of climate study and the comparison of data for different years until such time as series have been collected in most ocean areas that are long enough for annual cycles of water mass characteristics to be reconstructed.

Long-term series of hydrological measurements throughout the entire water column exist only for a few fixed stations or sections. Systematic observations of the hydrological section along the Kola meridian (33.5°E, 70.5-72.5°N) have been conducted since 1900 (39). The CALCOFI programme of standard sections across the California Current has been in operation since 1949. From 1949 to 1960, monthly surveys were carried out every year; from 1961 to 1969, quarterly surveys every year; and from 1969 to 1981, monthly surveys once every three years (for a review of the findings, see 56). Since 1949, observations have been made on weather ships, first in the Atlantic and then in the Pacific as well (85, 90; see also 29). The PANULIRUS hydrostation near Bermuda has been conducting deep-sea measurements since 1954 (147).

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* Some of the temperature measurements of the upper 2,000 m of the ocean were carried out by ships of opportunity which previously used bathythermographs and now, for the most part, use expendable bathythermographs (XBT).

Until the early 1960s when conductive and inductive salinometers were introduced, measurements of water salinity were not outstandingly accurate, which somewhat complicates the study of water salinity (129).

Only a comparatively limited number of conclusions and estimations of a climatological character have thus far emerged from data from the aforemetioned and other sources. Evidence of long-term changes occurring in the ocean depths has, for the most part, been studied from measurements made by the research vessel PANULIRUS (46, 89, 109, 110, 125, 134), weather ships (58, 63, 129) and from the comparison of data collected by the GEOSECS and TTONAS expeditions (91, 114, 131) during the International Geophysical Year. The results of the comparison of different deep-sea measurements are presented in 73, 125 and 146. The spectrum of long-period fluctuations of water temperature from data of deep-sea observations in the Barents Sea and near Bermuda is given in 71, 111, 148 and 149. We shall discuss some of these results below from the standpoint of the climatological importance of T-S characteristics of the water mass of the ocean. Worthy of special mention is the conclusion regarding the climatic stability of T-S characteristics of the 'eighteen degree water' in the North Atlantic (125). As mentioned above, against a background of general stability, instances of long-term (8-9 years) shifts of T-S characteristics of these waters with a gradual return to the norm were observed. This raises hopes that the long-term monitoring of T-S characteristics of the 'eighteen degree water' in the Atlantic and, perhaps, of the 'sixteen degree water' in the northern part of the Pacific will prove to be very useful indicators of trends in climate change.

At the present stage of our physical understanding of the dynamics of the general circulation of ocean waters, the conclusion naturally suggests itself that there is a climatic connection between the interannual variability of the baroclinic structure in the ocean and the interannual variability of the integral transport of water by large-scale currents (143, 144). The same conclusion was reached earlier with respect to seasonal variability (6, 98). What White (144) regards as significant for climatological analysis is the so-called baroclinic potential energy BPE, defined as:

$$\mathrm{BPE} = \rho_0 g \int_{500\,\mathrm{m}}^{0} \int_{500\,\mathrm{m}}^{z} \alpha \, dz \, dz$$

where α = specific volume and z = vertical co-ordinate, positive downwards. The relationship between the horizontal gradient of this value and the integral transport M is defined by the geostrophic relation:

$$\vec{M} = \frac{\vec{K} \times \nabla_H \mathrm{BPE}}{f \rho_0}$$

where f = Coriolis parameter, ρ_0 = average density, $\vec{K}$= vertical unit vector. Meyers (98) used as a BPE indicator the depth of the 20° isotherm and its deviation from the mean annual value. The principal value of the works cited lies in the fact that they demonstrate the possibility of climatic analysis of the variability of the field of ocean currents* based on the monitoring of T(z) or S(z) profiles of their integral characteristics (and, in the simplest case, the depth of the selected isotherm) at one or more representative fixed points.

Complex processes of ocean-atmosphere interaction play a part in the formation of the thermohaline characteristics of ocean water not only near the surface but also in the entire column. The conclusion concerning the connection between the character of a T-S curve typical of an ocean basin and the global transport of heat and atmospheric humidity in the atmosphere above it (130) is interesting in this context. The meridional transport of heat and moisture in the atmosphere must be in balance with the meridional transport of heat and salt in the ocean. Therefore, in a number of works (78, 79, 137, 141) meridional transports of heat and fresh water in the ocean are assessed on the basis of these similar transports in the atmosphere that have been most thoroughly studied. Judging from the rate of flow of fresh water in the atmosphere, F, and from the transport of heat in the ocean, H, as determined from meteorological (or any other) data, one can calculate the rate of flow of water masses with given T-S characteristics. The trans-oceanic latitudinal section "A" is broken down into sub-areas A_i, each of which consists of water of a specific T-S class with temperature (T, T+ Δ T) and salinity (S, S+Δ S). Mean meridional speed v (S, T) of the water of a given T-S class is considered constant. The transport of the mass of salt and heat across oceanic section A can then be written in the form of simple sums (130):

$$\Sigma M_i = F$$

$$\Sigma M_i \bar{S}_i = 0$$

$$\Sigma M_i \bar{T}_i = H/C_p$$

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* For more on currents, see the later section on climatic variability of oceanic currents and its indices.

where $\bar{T}_i$ and $\bar{S}_i$ = weighted average temperature and salinity in sub-area A_i, $M_i = \rho_i v_i A_i$, C_p = heat capacity, and ρ_i = water density in the presence of S_i and T_i data. From the known T_i, S_i, H and F values, the transport of the water mass M_i in the i^{th} layer of section A can be calculated. Obviously, the number of water masses should not exceed three. On average, water moving across a latitudinal section to the north is ΔT warmer and ΔS less salty than water moving south. The relation $\Delta T / \Delta S$ is expressed as:

$$\Delta T / \Delta S = r' \equiv H / C_p SF$$

where S = the average salinity of water moving north (130). Magnitude r', within the limits of permissible error, should be equal to the slope ($dT/dS \equiv r$) of the linear section of the mean T-S curve. The correctness of these conclusions was verified for the five degree zone at Lat. 40°N in the northern part of the Atlantic (130). Thus, the climatological importance of typical profiles T(z) and S(z) also lies in the fact that a modified form of these data can be used to characterize meridional water exchange in the ocean and the global transport of heat and atmospheric humidity.

It was recently ascertained (123, 28, 12) that the density ratio

$$R_\rho = \frac{\alpha\, \partial T / \partial z}{\beta\, \partial S / \partial z}$$

where

$$\alpha = \frac{1}{\rho} \frac{\partial \rho}{\partial T}\bigg|_{S,P} \qquad \beta = \frac{1}{\rho} \frac{\partial \rho}{\partial S}\bigg|_{T,P}$$

and ρ is sea water density, is a very conservative value for some layers in all the three major oceans: the Atlantic, Indian and Pacific. It was found that the T-S curves of these layers, corresponding on the whole to the central oceanic of "mode" water masses (the 200-800 m layer in the Atlantic), were governed by the strict correlation R_ρ = const = c (Fig. 4), with c = 1.9-2.0 in the Atlantic and Indian oceans, c = 2.6 in the southern part of the Pacific, and c = 3.8 in the northern part of the Pacific (12). Deviations from these values within the layers considered are rare and insignificant. The highly consistent behaviour of T-S curves in these layers is connected with the homogenizing effect of diapycnic mixing due to thermohaline convection of the salt finger type which develops under the favourable conditions created by the sinking, along the slanting isopycnals, of the waters of the oceanic upper layer which have become salty through evaporation. It is no accident that c = 3.8 in the freshest water from the surface of the northern part of the Pacific and decreases by one-half (c = 1.9) in areas of the Atlantic and Indian oceans where evaporation from the surface and salinity are at a maximum. The relationship between R_ρ values in 'mode waters' and the climatic conditions under which these waters begin to form is quite obvious. It is possible that R_ρ values undergo interannual fluctuations or display long-term trends, but for the moment, this is a closed book to us.

It is clear from the above that the saline regime of the ocean surface waters can have a decisive influence on the thermal regime of the whole water mass of the ocean. Therefore it is quite reasonable to assume that slow climatic shifts in the interaction and energy exchange between the atmosphere and the ocean can affect the thermal regime of deep-sea waters through the saline regime of its surface waters. It is interesting to note in this connection that the variability of deep-sea water temperature (DWT), according to paleo-oceanographic data (35), was much greater, in the comparatively recent geological history of the Earth, than that of SST. In Schopf's opinion, over a representative time period of 100-200 million years, DWT fluctuations amounted to as much as 10°C. Over the same period, SST changes ranged between 1 and 4°C. It is difficult to imagine that such DWT fluctuations were not related to very substantial disturbances of the vertical stability of oceanic waters and, consequently, of their saline structure. Long-period and reliable monitoring of DWT changes can therefore be of great importance for climatic studies.

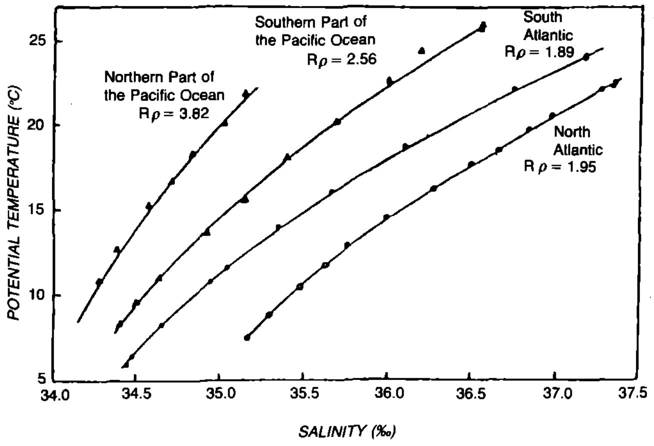

Figure 4. Forms of the T,S relationship in the central waters of various oceans after (123).

In addition to the considerations set out above, the monitoring of T(z) and S(z) profiles at specially selected points of sections is essential for the development of time series data on the heat and salt contents of the active upper ocean layer. That, in turn, would make it possible to study temporary changes in the heat and moisture balances in the ocean-atmosphere system. In particular, the thermal content of the active ocean layer is an extremely important characteristic and merits special examination as a climatically significant parameter.

Heat content of the active ocean layer. On the basis of his analysis of a nine-year series of measurements carried out by the weather ship 'November', Emery (64) showed that the heat content of the 0-250 m layer depended more on temperature fluctuations in the 100-200 m level than on fluctuations in SST or in mean temperature in the 0-60 m layer. Hence the conclusion that the thermal content of the 0-60 m layer/depends on the local radiation balance and turbulent heat exchange with the atmosphere than does the thermal content of the 0-250 m layer. Emery regards the behaviour of the thermal content in the 0-250 m layer, which is independent of SST, as being due to variability in the vertical advection of heat. Analysing the data series of 10 weather ships in the Atlantic, Arkhipova (1) came to the conclusion that the horizontal advection of heat played an important role in the variability of the thermal structure of the active ocean layer. Both Arkhipova and Emery accompanied their analyses with calculations of the heat balance of the layer in question. In general, it can be said that their conclusions contain no fundamental differences or contradictions, in so far as differences between the effects of vertical and horizontal advection cannot be established from measurement of the water column at a single point. What Emery interpreted as the result of the variability of vertical speed w_D on a certain level D

$$w_D = - \left. \frac{\partial T / \partial t}{\partial T / \partial z} \right|_D$$

could also be the result of horizontal advection with speed u_D

$$u_D = - \left. \frac{\partial T / \partial t}{\partial T / \partial x} \right|_D$$

or a combination of both:

$$\left. \frac{\partial T}{\partial t} \right|_D = - w_D \left. \frac{\overline{\partial T}}{\partial z} \right|_D - u_D \left. \frac{\partial \bar{T}}{\partial z} \right|_D$$

Emery's study (64) contains no direct evaluation of the possible effect of horizontal advection. However, as shown earlier (30), both effects could be of the same order, at any rate for inertial and tidal periods.

What was said at the beginning of this section touches on the problem of selecting a lower limit for the active ocean layer that is climatically significant, i.e., a natural lower limit to the downward spread of climatic and interannual temperature fluctuations (fluctuations with time scales of one, two or more years), coupled to the ocean-atmosphere energy exchange. A diagram in Emery's article (64) shows the penetration of seasonal fluctuations in temperature at least to a depth of 150 m. Bjerknes (49), citing Patullo (108), considers that, taking into account the depth of penetration of seasonal fluctuation, one should select the 300 m level as the lower limit of the active layer for calculating climatic changes in the heat balance. Moreover, measurements should not be occasional; they must be carried out repeatedly at prescribed intervals to permit averaging, and hence elimination of the effect of internal waves.

Recently, the possibility of determining the thermal content of the upper mixed layer of the ocean by using data from satellite observations of surface manifestations of internal waves has been discussed by some authors (14, 100).

The climatic variability of oceanic currents and its indices. It has already been explained in section 2.3 that indirect monitoring of the variability of the flow rate of specific branches of general oceanic circulation (e.g., equatorial currents (98)) is possible on the basis of direct monitoring of the variability of the baroclinic structure of the ocean, inside the upper 1,000 to 2,000 metres. In theory, the choice of suitable indices for the rate of oceanic circulation is extremely wide and varied. For example, Uda (140) suggests an empirical connection between the maximum speed v max (in knots) on the axis of the Kuroshio current and the horizontal temperature gradient G_T (in °C for 10 nautical miles):

$$v \text{ max} = 2G_T - 1$$

This link was established and verified on the basis of extensive measurements in the area between 128° and 153°E longitude over eight years (1955-1962). The establishment of such links by way of preliminary research prior to the development of long-term monitoring programmes would help to make subsequent work on them significantly cheaper.

A further important aspect in the development of such programmes for currents is the selection of a region or point for regular long-term measurements. The intensive meandering and meridional displacement of the axes of such currents as the Gulf Stream or the Kuroshio mean that the variability in the velocity or integrated transport at a fixed point (on a fixed vertical) should differ fundamentally from variability in the natural co-ordinates of the actual current. A clear demonstration of this fact is contained in the work of T. Rossby (117). From this same point of view, the monitoring of the flow rate of a current (e.g., the Gulf Stream) within strict natural boundaries (for example, in the Florida Straits) is of much greater physical and climatic significance than monitoring any cross-section, the side limits of which are determined by fixed geographic co-ordinates. This means that the data mentioned in the literature on seasonal and inter-annual fluctuations in the flow rates of the Gulf Stream and the Kuroshio (e.g., 88, 94), obtained by the dynamic method for hydrological data at cross-sections, are only accurate to within 10-20% (117) and to 30 per cent or more in the opinion of other researchers. In the opinion of Knauss (92), most of the inaccuracies in the use of this method derive from imprecision in the definition of the right-hand (looking downstream) limit of the Gulf Stream. Clearly, this may also apply to the Kuroshio.

On the other hand, the range of seasonal and inter-annual fluctuations in the flowrates of major currents and, probably, the ranges characterising their long-term variability (climatic trends) are not so large. For the Florida Current, the range of seasonal variations is of the order of 10-15 per cent from the mean flow rate, equal to 29.5×10^6 m^3sec^{-1} (117), whereas variations in its rate over 70 years from 1890 to 1960 did not exceed 10 per cent (124). Clearly, the seasonal variations in the Northern Equatorial Current in the Pacific Ocean can vary on the order of 30-40 per cent from the mean flow rate of $(15 \div 16)x10^6$ m^3sec^{-1} (98). However, aliasing of high frenquency fluctuations may give an error of as much as 25 per cent, over and above the element of imprecision connected with definition of the boundaries of the current which was mentioned above. As most currents have no such ideal, clearly delineated natural boundaries (as the Straights of Florida at the beginning of the Gulf Stream), consideration should be given, whenever measurements are being made, to 'tying' the position of the profile to the natural co-ordinates of the current under study - the position of the mid-stream and the side limits, which may be unknown. In such cases, the operational information obtained from satellites may be the only source of such data. This information can be found in SST data obtained in the IR or UHF bands, or data on the sea-level topography obtained with the aid of a radar altimeter. In theory, as has already been said, data on sea level (e.g. 33, 57 and Fig. 2) or differences in level at points located on either side of the current under consideration (e.g., 38, 88) may say more about its variability than other types of indirect data. This is why special attention should be given to sea level monitoring.

Sea level. Variations in sea level are particularly sensitive to climatic fluctuations. Climatic trends in the values of this parameter are connected with changes in the system of global water exchange (16) and with the thermal expansion and contraction of water (65, 74).

Over one thousand shore and island stations are conducting observations on sea level at the present time. However, the identification of long-term trends is made difficult by the uneven distribution and comparatively short duration of the observations in most cases. Moreover, tectonic movements and sedimentation from rivers produce local trends comparable with the effects of eustatic and isostatic changes. Therefore, in spite of the large number of accumulated series, frequent use is only made of a small number of them, about 200 (16, 32, 33, 74). Some authors eliminate the effect of tectonic movements by averaging the data obtained over a given area. It was demonstrated in work 17 that the effect of vertical movement of sea coasts can be reduced practically to zero by averaging data for a coastal section with a length of the order of 10,000 km.

Standard measurements of sea level have been made for many decades at many stations. This would appear to be the explanation for the general agreement in the various works written on the subject as to the assessment of climatic trends. Thus Kalinin et al., (16) analyzed data from 126 stations between 1900 and 1964 and showed that there was a close link between sea level and anomalies in air temperature in the zone from 17° to 90°N latitude (2) when smoothed with sliding 5-year means (Fig. 5). They found that sea level lags 19 years behind temperature. The coefficient of correlation between them for such a lag was found to be 0.94. Gornits and Lebedev (74), obtained practically identical values for the lag and correlation coefficient (18 years and 0.8 respectively), combining measurements from 193 stations from 1880-1980 and correlating them with data on the temperature of the surface layer of air in the Northern and Southern hemispheres (76). A large part of this positive correlation resulted from a general rise in sea level and air temperature. But the authors of these works also give various climatic causes for the increase in sea level. Kalinin et. al. (16), consider that the main reason for the increase in level is a change in global water exchange. Gornits and Lebedev (28) note that the lag discovered corresponds, in order of magnitude, to the period of thermal relaxation of the upper layers of the ocean. Using calculations based on a linear model (76), they attribute 50 per cent of the observable rise in sea level to the thermal expansion of water (74). Etkins and Epstein (65) share this view. The positions of the authors of all of the above-mentioned works should be carefully reconciled in order to obtain a better understanding of the climatological significance of fluctuations in sea level.

This was what Barnett (45) was setting out to do when he considered the combined effect of the melting of the polar caps and the thermal expansion of the upper thousand-meter layer of the ocean from the first decades of this century to the 1960s. He utilized data on water temperature and salinity which was independent of the series of measurements of sea level. After analyzing the changes in the dynamic heights of the upper layer of water in the Atlantic, Pacific, and Indian Oceans, Barnett concluded that the rise in sea level was connected with the melting of the polar caps rather than with the general increase in SST. The connection to SST was considered in the analyses of Paltridge and Woodruff (107). Barnett (44) had doubts about these analyses. Barnett (45) also demonstrated that the combined effect of the melting of the polar caps and the increase in SST should have resulted in a much greater increase in dynamic heights than was actually observed. He also observes in the same work (45) that the possible effect of fluctuations in the rate of global oceanic circulation cannot be rejected when considering the causes for long-term changes in sea level.

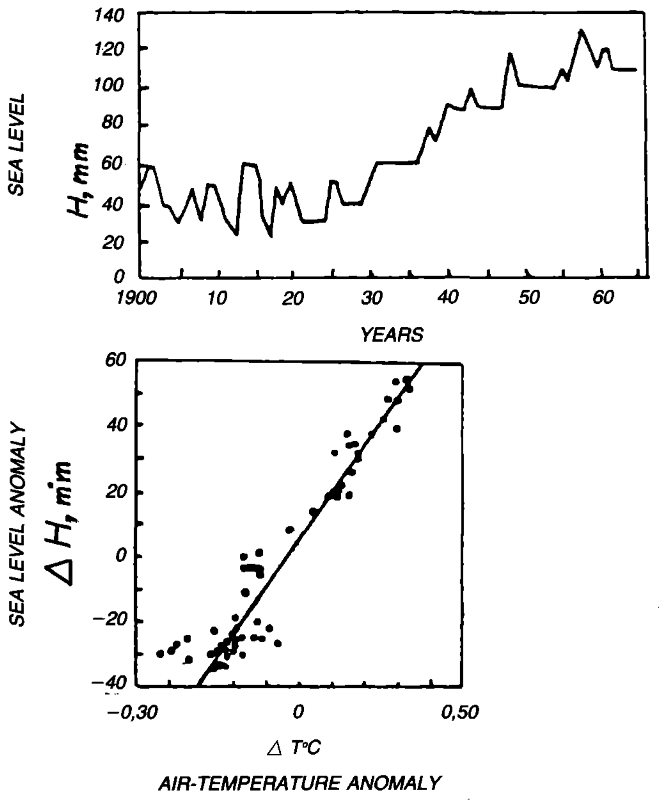

Figure 5. *Changes in sea level from 1900 to 1964 after (16) as related to air temperature anomaly in the zone 17°-90°N after (2).*

The works of Rossiter (118) and Privalsky, (32) who have evaluated the trends strictly on the basis of statistics, are the most outstanding of those dealing with fluctuations in sea level over a period of a century. Rossiter's work, which analyzes data on the level of the seas surrounding Europe, is also useful for providing a detailed technique for analyzing the extent to which variation in atmospheric pressure and the rise of continental masses (in this case the Finno-Scandinavian Shield) contribute to long-term climatic changes in level.

Among the most promising sources of climatological indices is the long-time record of sea level in the Pacific Ocean, where there is an abundance of islands with a developed network of sea-level stations. This network has been significantly extended during recent decades, and many researchers examining the variability of currents in the Pacific Ocean have drawn on the long-term data provided by this network. A historical and physical analysis of this question may be found in the recent work by Wyrtki (151). The monitoring of sea level in the islands of the Pacific Ocean also takes on considerable climatological significance in the context of research and prediction of the development of El Nino (151).

Sea level has also become a very promising parameter of the ocean from the climatological point of view by the possibility of remote monitoring with the aid of satellites. The satellite altimetry in prospect should make it possible to establish the topography of the free surface of the ocean with a degree of error no greater≤than ± 10 cm. It could thus ultimately provide regular information on the variability of all the main branches of general oceanic circulation.

But first, a fairly lengthy programme of technical improvement and auxiliary scientific research will have to be carried out in order to solve a large number of serious problems which are identified in (103). The most obvious of these are:

a) precise knowledge of the satellite orbit,

b) knowledge of the geoid (150),

c) elimination of the effects of tides and storm-sturges,

d) corrections for atmospheric water vapour and other factors.

Available experience (95) indicates, that in areas where the long-term average position of the mean surface can be calculated (by the dynamic method) from oceanographic data, departures in level from this mean surface determined by means of satellite radar altimeters are of genuine physical and climatological significance.

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2. The Continuous Plankton Recorder Survey

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Introduction

The survey is based on quasi-synoptic observations, at monthly intervals of the plankton of the North Atlantic, North Sea, Norwegian Sea, Irish Sea, English Channel and the Bay of Biscay, using merchant ships and Ocean Weather Ships as "Ships of Opportunity" to tow Continuous Plankton Recorders (Hardy, 1939). The main objective is to investigate the variability in distribution and abundance of the plankton (including fish eggs and larvae) and their response to changes in the environment. The results have also been used for the following purposes:

(a) to produce a plankton atlas of the North Atlantic and adjacent seas;

(b) to provide information about the biology of the dominant species of the plankton (distribution, population dynamics, generations times, production, etc.);

(c) to maintain a monitoring function of the "health" of the seas.

The Continuous Plankton Recorder used in the survey in 1985 is very similar to that described by Hardy (1936, 1939). Indeed, since 1948 the fundamental design has not been changed and methods of analysis of the samples have been standardised so we have time-series of 38 years (1948-1984) of data which have been collected, analyzed and processed in exactly the same way.

A regular survey of the southern North Sea using Plankton Recorders towed by merchant ships was started in 1931 by Sir Alister Hardy from the Department of Oceanography of the University of Hull. In 1938 the survey was extended to the whole of the North Sea and in 1939 by a route in the north-east Atlantic between the north of Scotland and Iceland. There was no sampling during the second world war (1939-1945) but the survey was restarted in 1946 and expanded into the north-east Atlantic in 1947 using Ocean Weather Ships. After 1958 the survey expanded progressively westwards to the coasts of Greenland, Canada and the USA. In 1968, thirty-three merchant ships and weather ships of eight nations towed Plankton Recorders for a total of 120,000 miles.

The survey is presently supported by the British Treasury through the Natural Environment Research Council and the Ministry of Agriculture Fisheries and Food. In the past it was financed by the Development Fund of the UK and by contracts with the United States Department of the Navy, Office of Naval Research.

Methods

Sampling. Continuous Plankton Recorders (Fig. 1) can be towed at speeds of between 8 and 25 knots with sufficient wire in the water so that it samples at a depth of 10 m. Water enters through an opening of 1.27 cm square at the front of the machine and passes along a tunnel across which a band of bolting silk is wound continuously; the silk grade is 60XXXX with a mesh aperture of about 285 u by 310 u. The silk is wound through the machine in proportion to the distance travelled so that it can be divided into sections each representing, in the present survey, 100 miles of towing (equivalent to 3 m^3 of water filtered).

In 1985 Plankton Recorders were towed at monthly intervals, as far as possible, on the routes shown in Fig. 2, by ships of eight nations (Denmark, France, Federal Republic of Germany, Iceland, Republic of Ireland, Netherlands, Norway and the United Kingdom). The routes on which Recorders were towed in each year from 1948 to 1982 are published in the Annls. biol. Copenh., vols 5 to 39, together with summaries of the distribution and abundance of the plankton of the north-east Atlantic and the North Sea for that year. Further details of the routes sampled during the period 1958 to 1968 and numbers of samples taken are given in Edinburgh Oceanographic Laboratory (1973).

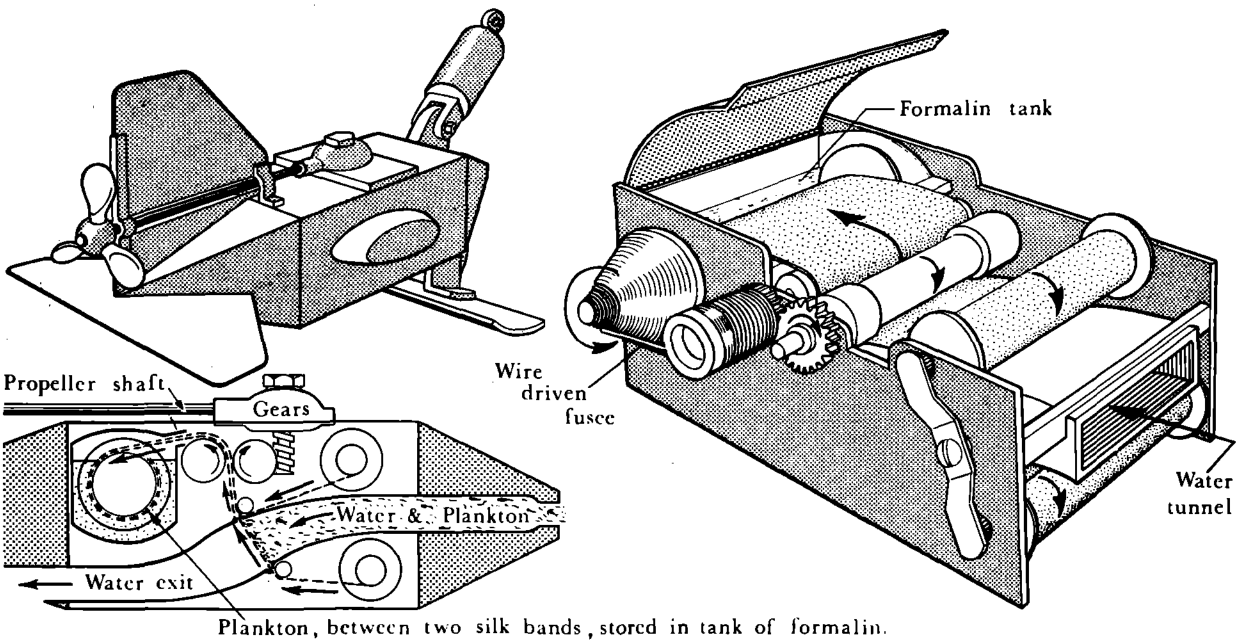
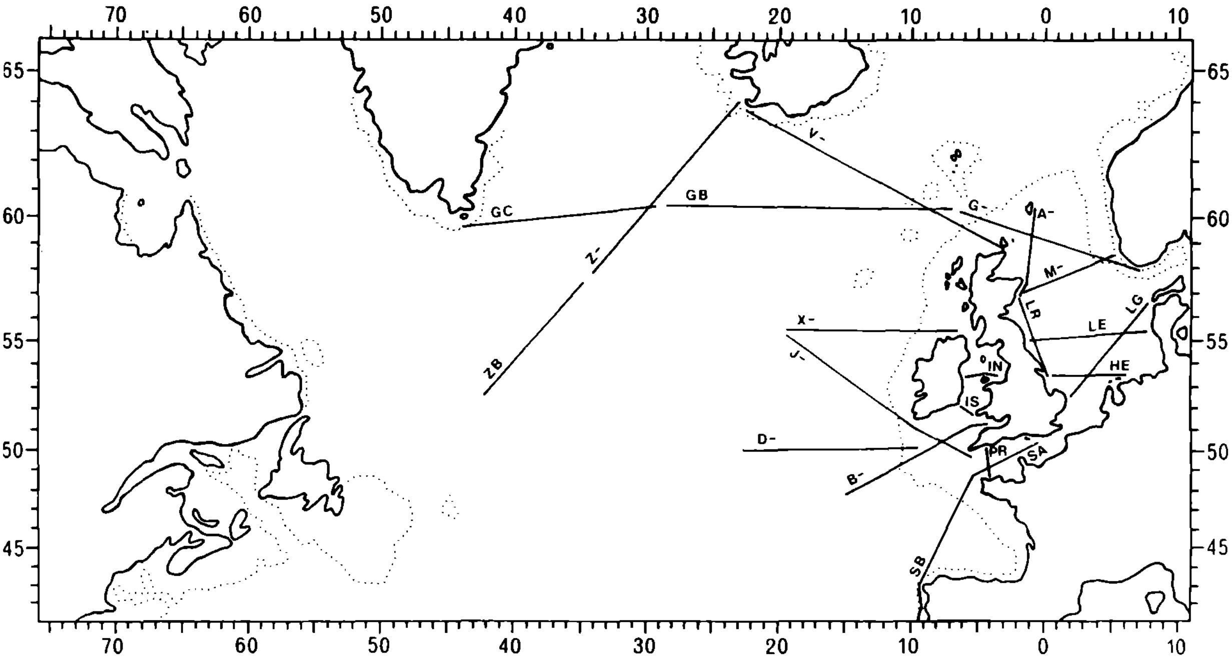


***Figure 1.** Simplified diagrams of the Continuous Plankton Recorder. Top left, as seen from the right rear. Bottom left, a section showing the paths of the two bands of bolting silk. Right, the inside mechanism shown from the right front (taken from Glover, 1962).*



Continuous Plankton Recorder Survey 1985

***Figure 2.** A chart of the routes along which Continuous Plankton Recorders were towed during 1985; they are identified by code letters.*

Analysis. The methods of analysis of the samples have been described by Rae (1952), Colebrook (1960) and Robinson and Hiby (1978). Samples are subjected to a standard routine analysis and the organisms are identified and counted on the silk.

The abundance of phytoplankton is estimated in two stages. A measure of the total phytoplankton is obtained from a visual assessment of the coloration of the filtering silks. The samples are assessed according to three degrees of green-ness, each of which is assigned a numerical value based on acetone extracts of samples in each category. The abundance of each species or other taxonomic entity is estimated by recording its incidence in a sub-sample of 20 fields using a microscope with a field diameter of 0.295 mm. Only a small proportion of the phytoplankton is retained by the silk used in the Recorder and unarmoured dinoflagellates tend to disintegrate in the formalin used as a fixative and preservative. Nevertheless, the data provide observations of the abundance of species which are sensitive to changes on a monthly time-scale and they have revealed regular and meaningful patterns of variability in relation to the time and space scales of the survey.

The zooplankton are also counted and identified in two stages. First, a staggered microscope traverse is taken across the filtering and covering silks, using a field diameter of 2.06 mm, and the numbers of the smaller organisms are counted. Secondly, larger organisms are counted by eye, picking them off the silk to confirm identification when necessary. The counting is based on a roughly logarithmic series of categories (Colebrook, 1960) to ease the problems of analysing large numbers of samples. The level of identification is a matter of expediency, to variety, species, genus or family depending on the existing state of knowledge, problems of identification and importance. A list of the organisms that have been observed in the samples is given in Edinburgh Oceanographic Laboratory (1973).

Data processing. Data are stored on magnetic tape as category codes for each entity in each sample and these data can be retrieved and processed in a variety of ways with respect to time and space. In the routine data processing the samples are allocated to rectangles of 1^{o} Lat. by 2^{o} Long. and these are aggregated into a set of standard areas shown in the chart in Fig. 3 (Colebrook, 1975). The means of log-transformed counts for each species or other entity are calculated for each month for each sampled rectangle and standard area. From these, charts of distribution per month, per year or for longer periods can be produced and graphs of seasonal and annual fluctuations in abundance can be plotted.

Results

Kendal (1973) suggests that time-series of data extending over periods of years may frequently be considered as a mixture of four components: a trend or long-term

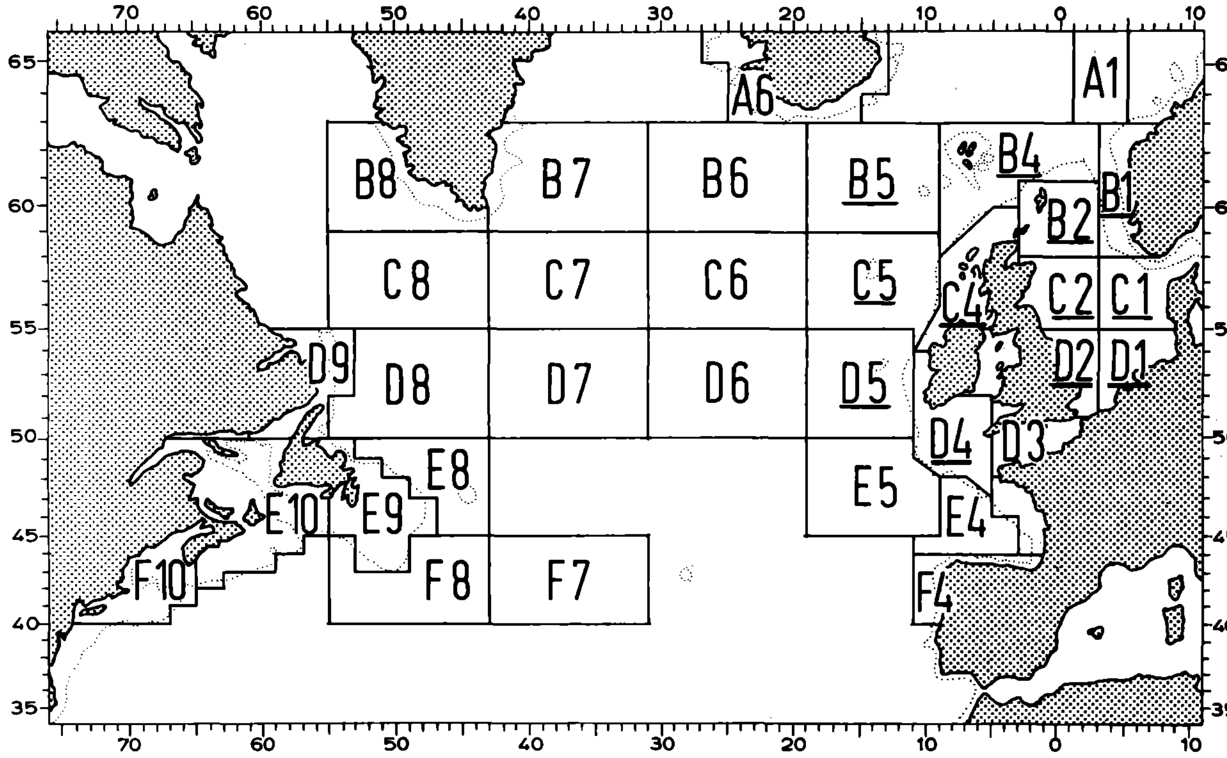


Figure 3. A chart of the North Atlantic showing the set of standard areas used in routine processing of the survey data. A list of the areas together with the years for which data are available are given in Table 1. A sub-set of the areas, for which data are presented in Figs. 4 to 8, are underlined.

movement, fluctuations about the trend, a seasonal component and a residual or random element. Many time-series also exhibit persistence when the value at a particular time is a function of the value at some previous time; persistence coupled with irregular or random effects can produce apparently systematic long-term fluctuations.

The data provided by the Continuous Plankton Recorder survey consists of estimates of average numbers of planktonic organisms in areas of the north-east Atlantic and the North Sea at monthly intervals for the period 1948 to the present. The data, therefore, contain the basic random errors involved with sampling ; also, plankton organisms exhibit considerable small scale spatial variability (see, for example, Colebrook, 1969, Haury et al, 1978). In the survey data these sources of variability are reduced as much as possible by the configuration of the sample, which is a cylinder of water 1.27 cm in diameter and 10 miles long, by logarithmic transformation of the original counts and by averaging the counts for fairly large numbers of samples. The resulting estimates still contain a proportion of random variability that has to be regarded as "noise" in the time-series.

The survey covers part of the temperate zone of the ocean which is subject to all the influences of a marked seasonal variation in the altitude of the sun. Nearly all the species show considerable seasonal variations in abundance reflecting the seasonal cycle of growth and mortality. Over most of the area, winter is a season of little or no growth. The amplitudes of the seasonal changes in abundance are in general far larger than any year-to-year changes.

By their very nature, populations of organisms exhibit persistence, the extent of which varies considerably from species to species depending largely on generation time. Most phytoplankton species have generation times of a few days while most of the smaller zooplankton species have generation times of a few weeks and, of the larger zooplankton, few live longer than a year. Colebrook (1981, 1982) has shown that persistence associated with generation times of a few weeks can influence abundance over periods of years.

It is against this background of "noise", seasonal variation and the effects of persistence that long-term signals in the form of trends and shorter period fluctuations have to be detected and analysed. The period covered by the observations, from 1948 to 1984 is, by the standards of time-series analysis, relatively short and the results of such analyses have to be treated with some caution. On the other hand, data are available for several areas (Fig. 3) and for some 24 species of phytoplankton and 25 of zooplankton. This means that well over 400 time-series are available, large

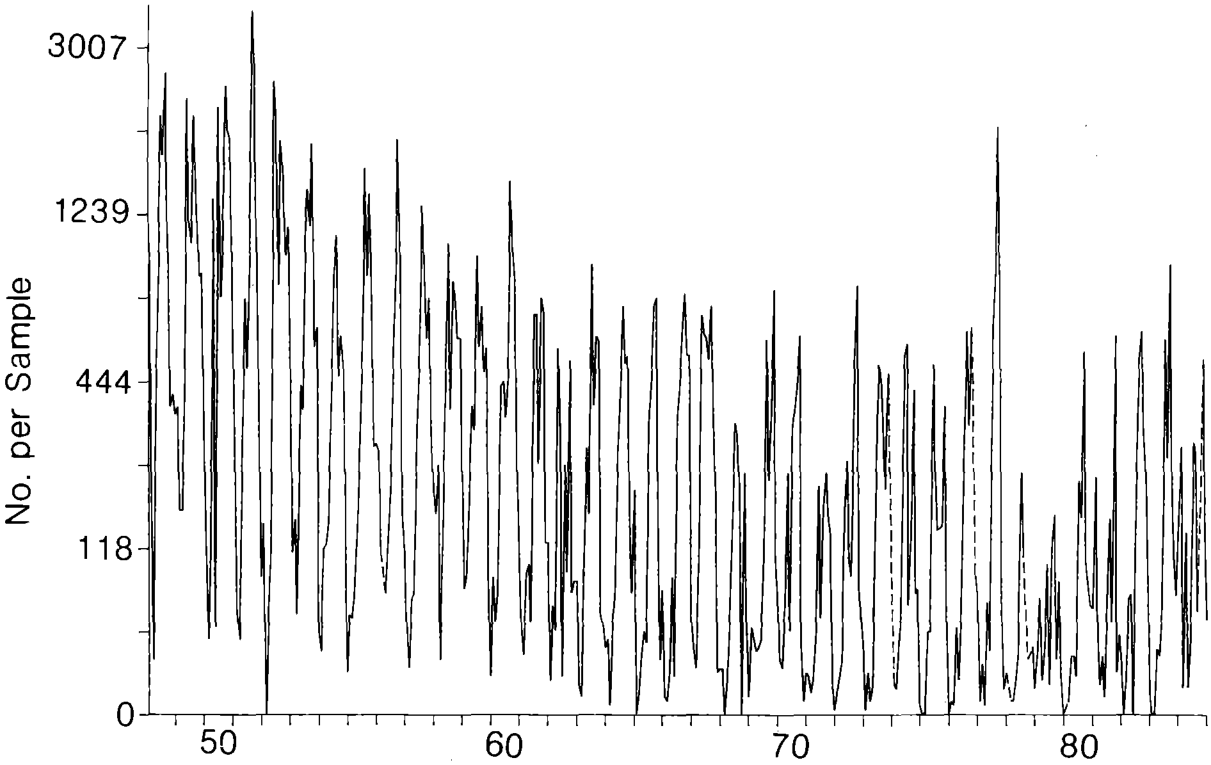


Figure 4. A graph of monthly means, as numbers per sample of 3 m, of the abundance of Pseudocalanus elongatus *for the period 1948 to 1984 and for the area C1 (see Fig. 3). A dashed line indicates missing data.*

numbers of analyses can be performed and recurrent patterns and frequency peaks can be searched for in these data.

Within the confines of this paper it is clearly not possible, nor is it necessary, to present all the results that have been obtained. All that will be attempted here is to present examples and summaries of the more significant findings.

Fig. 4 is a plot of monthly means, for the period 1948 to 1984, for the copepod Pseudocalanus elongatus for the eastern central North Sea (area C1 in Fig. 3). This graph gives a general indication of the amplitude of the seasonal cycles relative to the year-to-year variability. Fig. 5a contains graphs of the annual means of P. elongatus for each of the areas shown in Fig. 3. In most of the areas there is a clear downward trend in abundance which is highlighted by fitted fifth-order polynomials. Fig. 5b contains histograms of the power spectra of each of the time-series shown in Fig. 5a. It is clear that a high proportion of the variability is associated with long wavelengths.

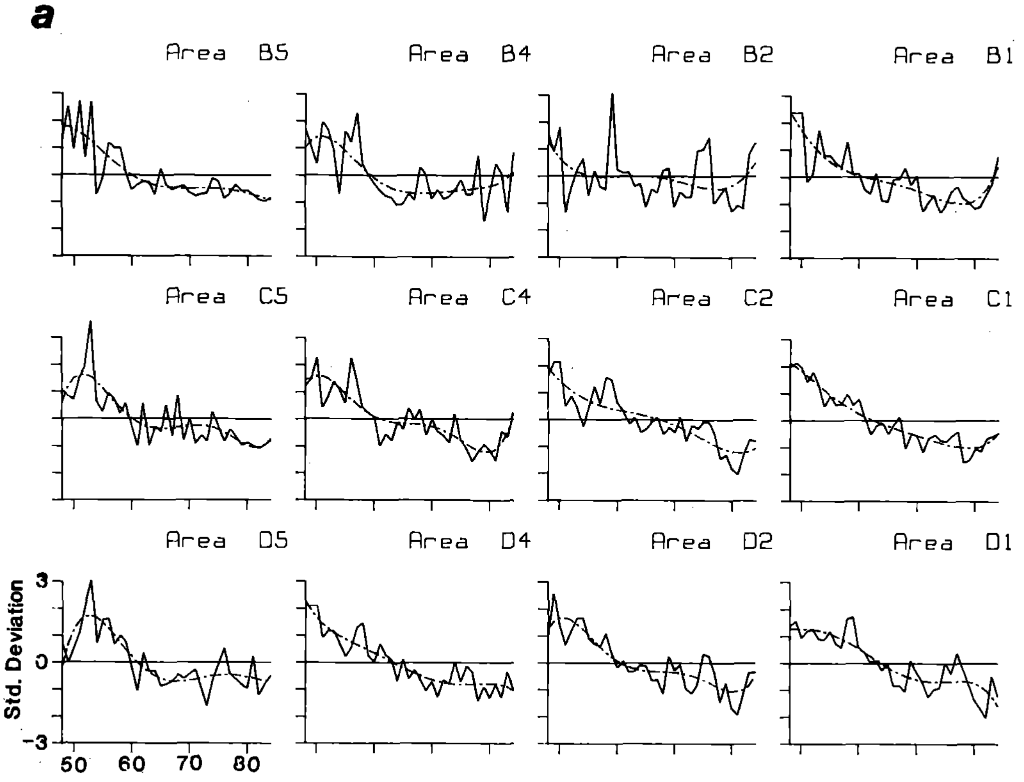
Fig. 5 indicates that there are considerable similarities between the patterns of year-to-year changes in abundance in each of the areas which can be conveniently summarised using principal components analysis. Fig. 6a shows a graph of the first principal component of each of the time-series of data shown in Fig. 5a, the long-term trend is highlighted by a fitted polynomial and its power spectrum is given in Fig. 6b.

The long-term trend is not restricted to this one species. Fig. 6c shows the first principal component, together with a fitted polynomial, of the annual fluctuations in the abundance of 18 zooplankton taxa for the eastern central North Sea (area C1 in Fig. 3). It is obviously similar to the component for P. elongatus for all the areas (Fig. 5a). The components plotted in Fig. 6 are just two examples illustrating marked coherence between areas and between species with respect to annual fluctuations in abundance, the details of which are given by Colebrook (1978). The main feature of the coherence is the long-term trend which is exhibited by most of the zooplankton in a large area of the North Sea and the north-east Atlantic representing a wide range of hydrographic regimes, ranging from shallow unstratified waters in the southern North Sea to deep, stratified open-ocean areas. In addition, there are no obvious relationships between the species with respect to the long-term trend that can be attributed to differences in life-history or trophic habit or seasonal cycle. It would appear that the trend has to be attributed to more or less uniform environmental forcing over a very large area and has to be looked for in the realm of large-scale climatic changes.

Lamb (1971) proposed a classification of the main atmospheric pressure patterns over the UK and produced tables of daily assessments of the weather type from 1861 to 1971. These data have been maintained and published by the Climate Research Unit of the University of East Anglia. For comparisons with the plankton, the types proposed by Lamb have been reduced to five, respectively, anticyclonic, cyclonic, westerly, easterly and northerly. Annual mean frequencies of each of these types have been calculated for the period 1948 to 1984.

Fig. 7a shows a plot of the first principal component for all the zooplankton species in area C1 (Fig. 3) superimposed on tha annual fluctuations in the frequency of westerly weather over the UK. Also included are plots of coherence and phase spectra derived from a maximum-entropy cross-spectral analysis calculated by the method of Strand (1977). The two variables are positively coherent at the longest wavelenths and this is obvious in the plot of the variables. There is a second peak in coherence at a wavelength of about 3 years and the phase indicates a negative relationship with the westerly weather leading the plankton by about a quarter wavelength. The data presented in Fig. 7 are just one example of a complex pattern of relationships between the plankton and the frequency of westerly weather. The coherence between the long-term trends is fairly general while the relationship in the 3-year wave band is found for several species and predominantly but not exclusively in the North Sea. There is a similar relationship in the 3-year band between the plankton and sea surface temperature in the North Sea from February to July (Colebrook, in press).

There are two problems in the interpretation of the relationship between the plankton and the frequency of westerly weather. Firstly, the phase lag in the negative relationship in the 3-year wave band; this occurs fairly consistently in the region of a quarter wavelength and appears to be due to persistence in the plankton data. Experiments with a simple model suggest that given persistence in the size of a population a phase lag of about a quarter wavelength is what would be expected with forcing at a wavelength of about 3 years (Colebrook, in press).



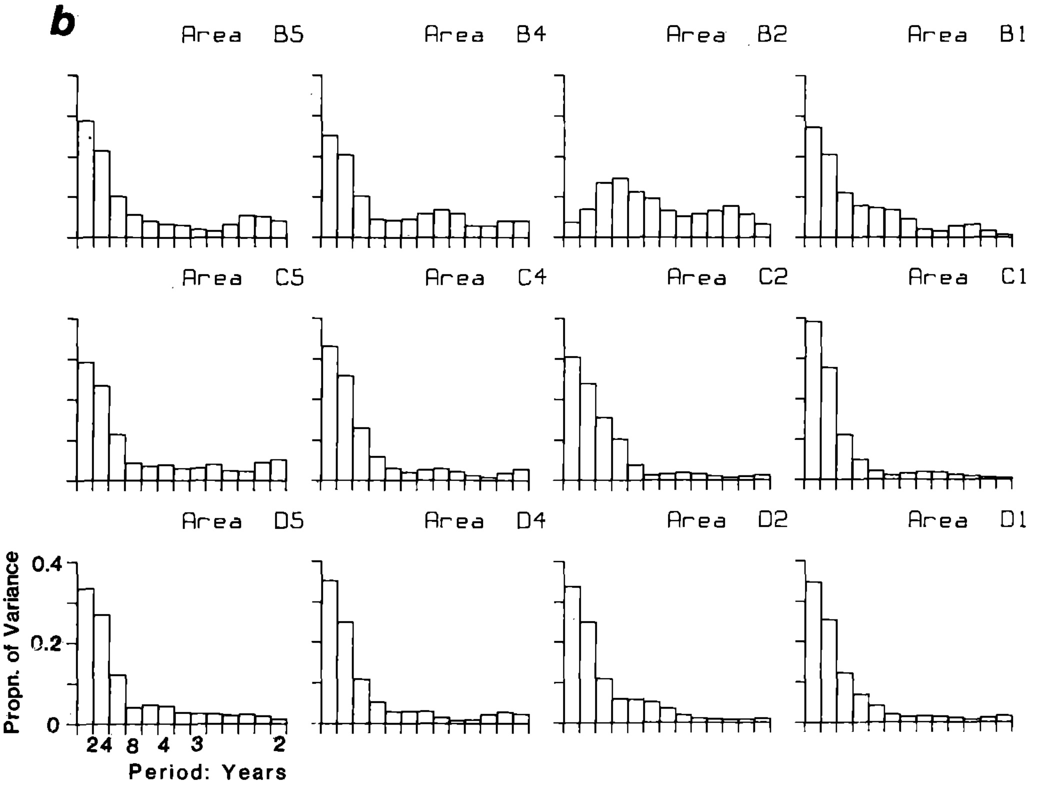


***Figure 5a.** Graphs of annual means of abundance of* Pseudocalanus elongatus *(continuous lines) for each of the well-sampled areas shown in Fig. 3. Each variable is reduced to zero mean and unit variance and in each graph the long-term trend is highlighted by a fitted fifth-order polynomial (broken lines).*

***Figure 5b.** Histograms of the power spectra, with maximum lags of 12, of the data plotted in a.*

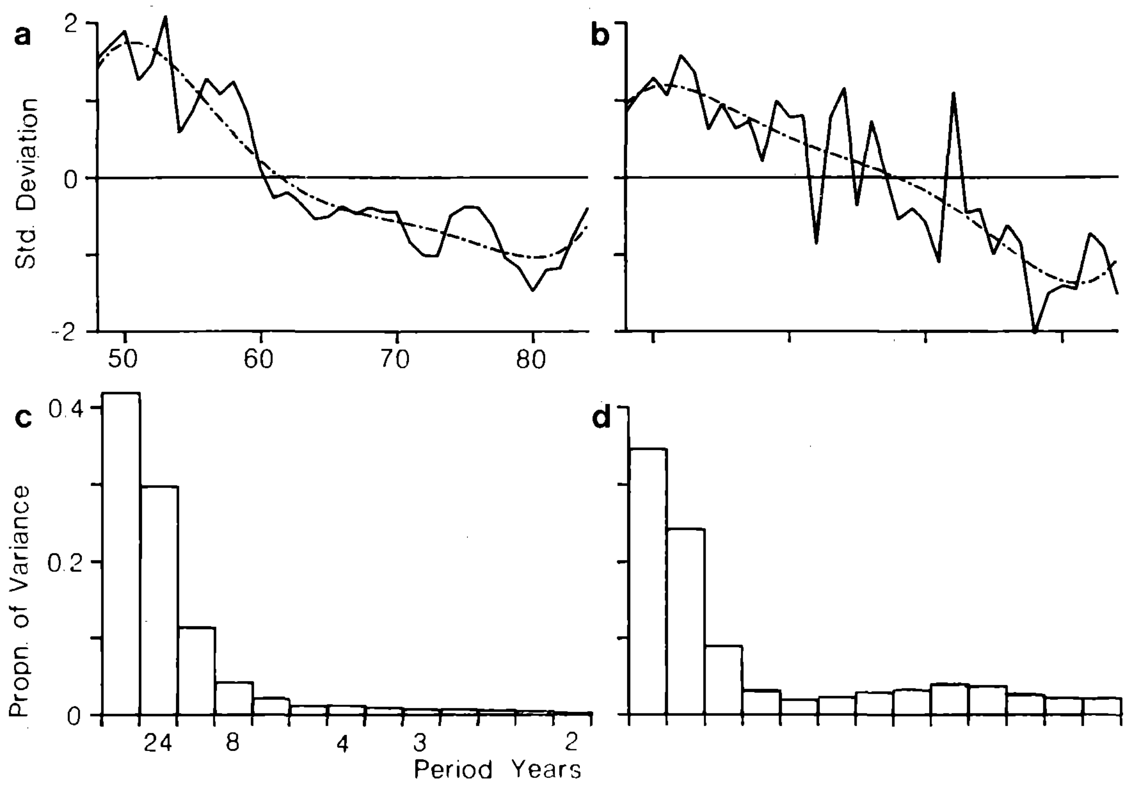


Figure 6

a. *A plot of the first principal component (continuous line) of all the variables plotted in Fig. 5a. The component has been reduced to zero mean and unit variance and the long-term trend is highlighted by a fitted fifth-order polynomial (broken line).*

b. *A histogram of the power spectrum, with a maximum lag of 12, of the component plotted in a.*

c. *A plot of the first principal component of the annual fluctuations in the abundance of all the zooplankton species for area C1 (see Fig. 3). The format is the same as in a.*

d. *A histogram of the power spectrum, with a maximum lag of 12, of the data plotted in c.*

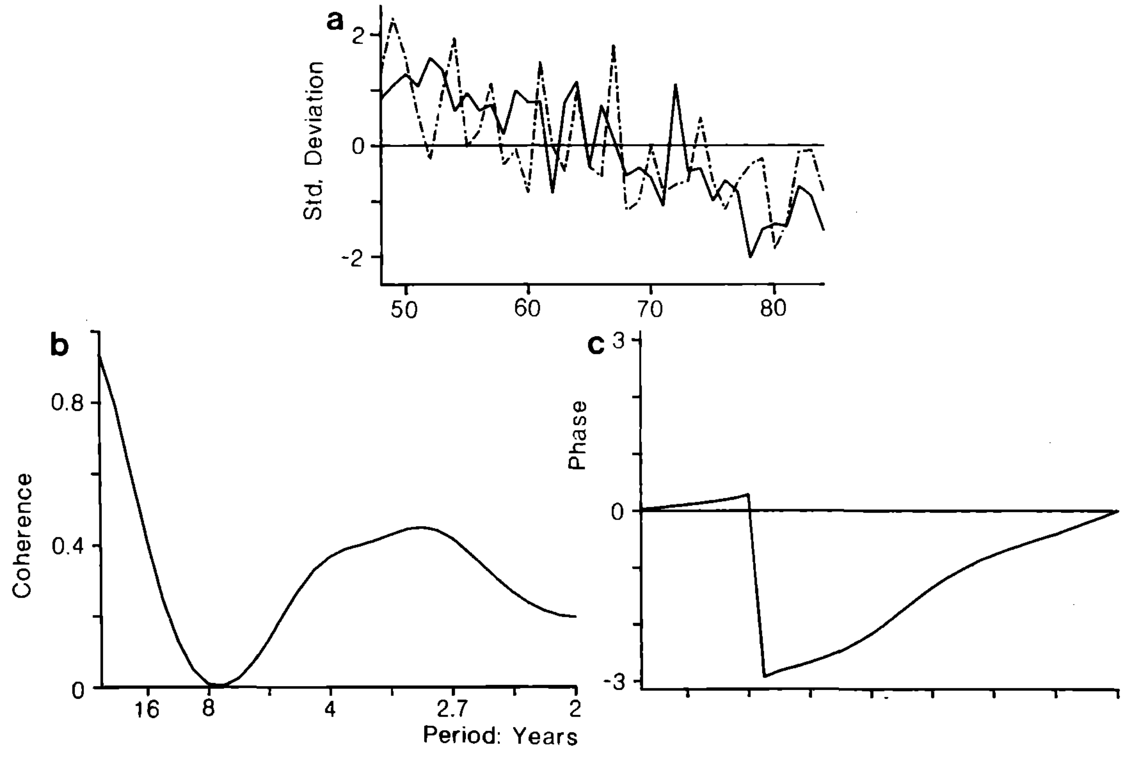


Figure 7

a. *A plot of the first principal component (continuous line) of the annual fluctuations in the abundance of all the zooplankton species in area C1 (the same data as in Fig. 6c) superimposed on the year-to-year variability in the frequency of westerly weather over the UK (broken line). Both variables are reduced to zero mean and unit variance.*

b. and c. *Plots of the coherence and phase spectra respectively, derived from a cross spectral analysis of the data in a.*

The second problem is that in relation to the trend the correlation between the plankton and westerly weather is positive while in the 3-year wave band it is negative. It seems possible that this is produced by a seasonal differentiation in the effect of the forcing associated with changes in the frequency of westerly weather. Colebrook (1984) has shown that the long-term trend appears to have its origin in winter. The study was based on a rather limited data set being restricted to those areas and species for which the numbers in the samples in winter are large enough to provide reasonable estimates of year-to-year changes. However, the data indicate that the species are more coherent in winter and that the long-term trend accounts for a higher proportion of the total variability in winter than in summer.

The "noise" levels in the plankton data are such that it is not possible to detect any seasonal variation in the expression or amplitude of the 3-year periodicity, but Colebrook and Taylor (1984) have suggested that the variability in sea surface temperature in this waveband is probably related to surface heat exchange phenomena and is, therefore, more likely to be an effective forcing process in spring or summer than in winter. Given the variability in the hydrographic and biological regimes within the seasonal cycle, it does seem possible for a single forcing process to induce different responses in the plankton populations which will be detectable, provided the responses occur in different parts of the frequency spectrum.

There are indications that the long-term downward trend in the abundance of the plankton may be reversing; both of the components illustrated in Fig. 6 show signs of an upturn around 1980, as do most of the areas shown in Fig. 5. A more detailed account of the evidence is given in Colebrook et al, 1984. In the mid 1970s, there were also a few years when it looked as though the trend might be reversing. The signs were, however, restricted to the open ocean areas and proved to be temporary; the downtrend reappeared in the late 1970s. This brief period of increase in abundance may be related to a period of marked negative salinity anomalies in the north-east Atlantic in the mid 1970s (see, for example, Ellett and MacDougal, 1983). Fig. 8a shows a plot of the first principal components, for all the areas shown in Fig.

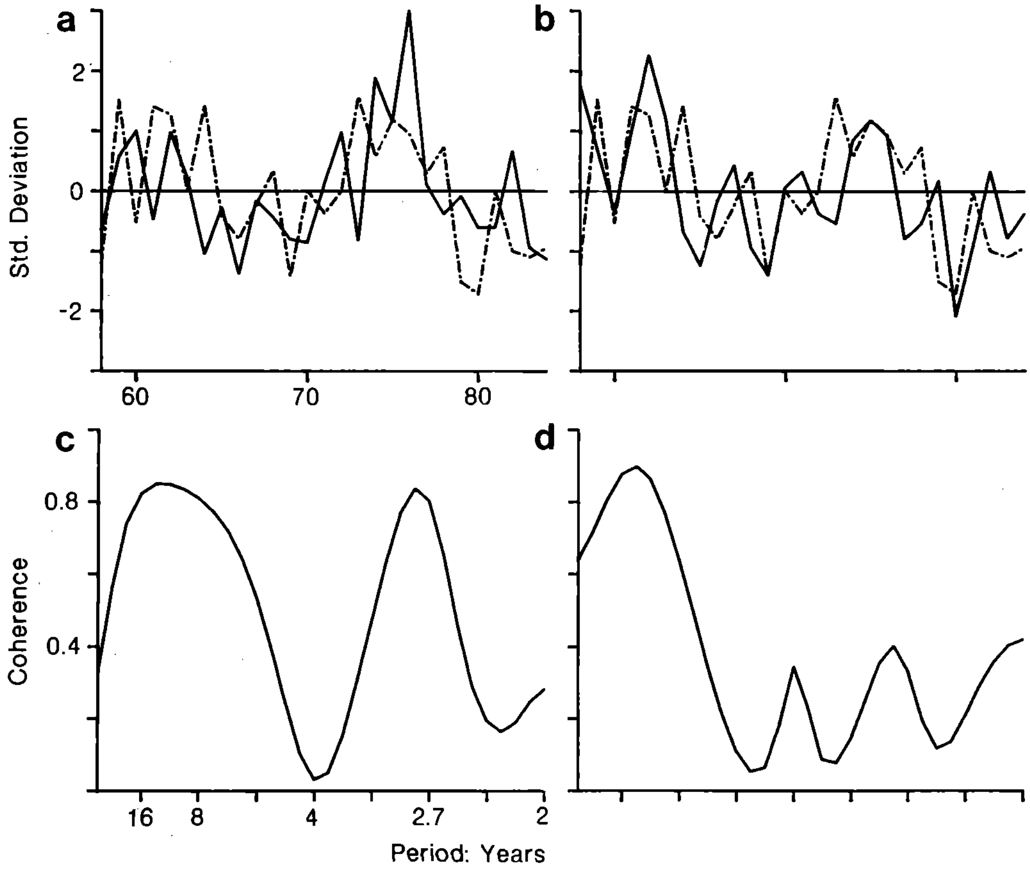


Figure 8. Graphs of the first principal components (continuous lines) of the annual fluctuations in abundance of a. Ceratium furca *and b.* Ceratium tripos *in all the well-sampled areas shown in Fig. 3, superimposed on the year-to-year variations in the frequency of cyclonic weather over the UK (broken lines). All the variables are reduced to zero mean and unit variance.*

The plots c. and d. are the coherence spectra derived from cross spectral analyses of the data plotted in a. and b.

3, of the annual fluctuations in the abundance of two dinoflagellate species, Ceratium furca and C. tripos, superimposed on plots of the variation in the frequency of cyclonic weather over the UK. The relationship between the Ceratium species and cyclonic weather is in fact negative but, for clarity, the cyclonic weather variable has been inverted. Fig. 8b shows plots of coherence spectra from maximum-entropy cross-spectral analyses of the data in Fig. 8a. These plots are two examples of relationships between five species of Ceratium and cyclonic weather which covers all the areas shown in Fig. 3 except for area D4, the Celtic sea. The relationship is characterised by coherence at wavelengths of about 10 years. The relationships are obviously negative but given the length of the time-series it is not possible to obtain precise estimates of phase.

Variability in this waveband has been widely recognised in data from the North Atlantic and the North Sea (Maximov, 1972, Southward et al, 1975, Colebrook & Taylor, 1979, 1984) but the physical and climatological processes involved have yet to be identified.

Conclusions

The time-series of data for the plankton of the north-east Atlantic and the North Sea for the period 1948 to 1984 exhibit several clear characteristics. There is considerable similarity between the data for different species and different areas, to the extent that the examples and summaries presented in this paper represent a significant proportion of the total year-to-year variability. There is clear structure within the time-series, represented by patterns of variability with clearly defined periodicities ranging from a pronounced long-term trend to wavelengths of a few years. Several of these patterns can be identified as the response to large-scale environmental forcing related to climatic factors, the nature of the response being influenced by persistence in the stocks. And, while the details of mechanisms and processes have yet to be established, in two cases the response may be associated with specific periods within the seasonal cycle.

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Table 1. *A list of the areas shown in Fig. 3 together with the years for which data are available.*

A1	1949 - 1981
A6	1956 - 1984
B8	1962 - 1975
B7	1957 - 1984
B6	1957 - 1984
B5	1948 - 1984
B4	1948 - 1984
B2	1948 - 1984
B1	1949 - 1984
C8	1959 - 1984
C7	1958 - 1984
C6	1958 - 1984
C5	1948 - 1984
C4	1948 - 1984
C3	1970 - 1984
C2	1948 - 1984
C1	1948 - 1984
D9	1959 - 1981
D8	1959 - 1984
D7	1959 - 1984
D6	1958 - 1984
D5	1948 - 1984
D4	1950 - 1984
D3	1957 - 1984
D2	1948 - 1984
D1	1948 - 1984
E10	1961 - 1976
E9	1960 - 1979
E8	1960 - 1982
E5	1952 - 1984
E4	1958 - 1984
F10	1961 - 1974
F8	1963 - 1973
F7	1963 - 1973
F4	1958 - 1984

3. Signature of El Niño in the East China Sea

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A mesoscale eddy was discovered in 1978 (Hu et al. 1980) in the northern East China Sea, which is more permanent in terms of time and locality and different from those occurring in the oceans. It is about 200 km in diameter, and generally colder and more saline near its center than its surroundings, as typically shown in Fig. 1.

There was only fragmentary data for the eddy study before 1975; for 1963, 1965, 1968, 1972, 1973 and 1974, only sparse data are available. Fortunately, however, there have been consecutive, at least bimonthly hydrographical measurements made since 1975 in the study area. Measured components are as follows: temperature, salinity, dissolved oxygen, and pH with Nansen bottle cast, wind speed and direction, and so forth. There is a thermal section shown in Fig. 2 along 32°N, which crosses the eddy and in which the interannual variability of the eddy can be easily seen. In what follows, the interannual variability of the eddy will be examined, instead of the seasonal variability which has been

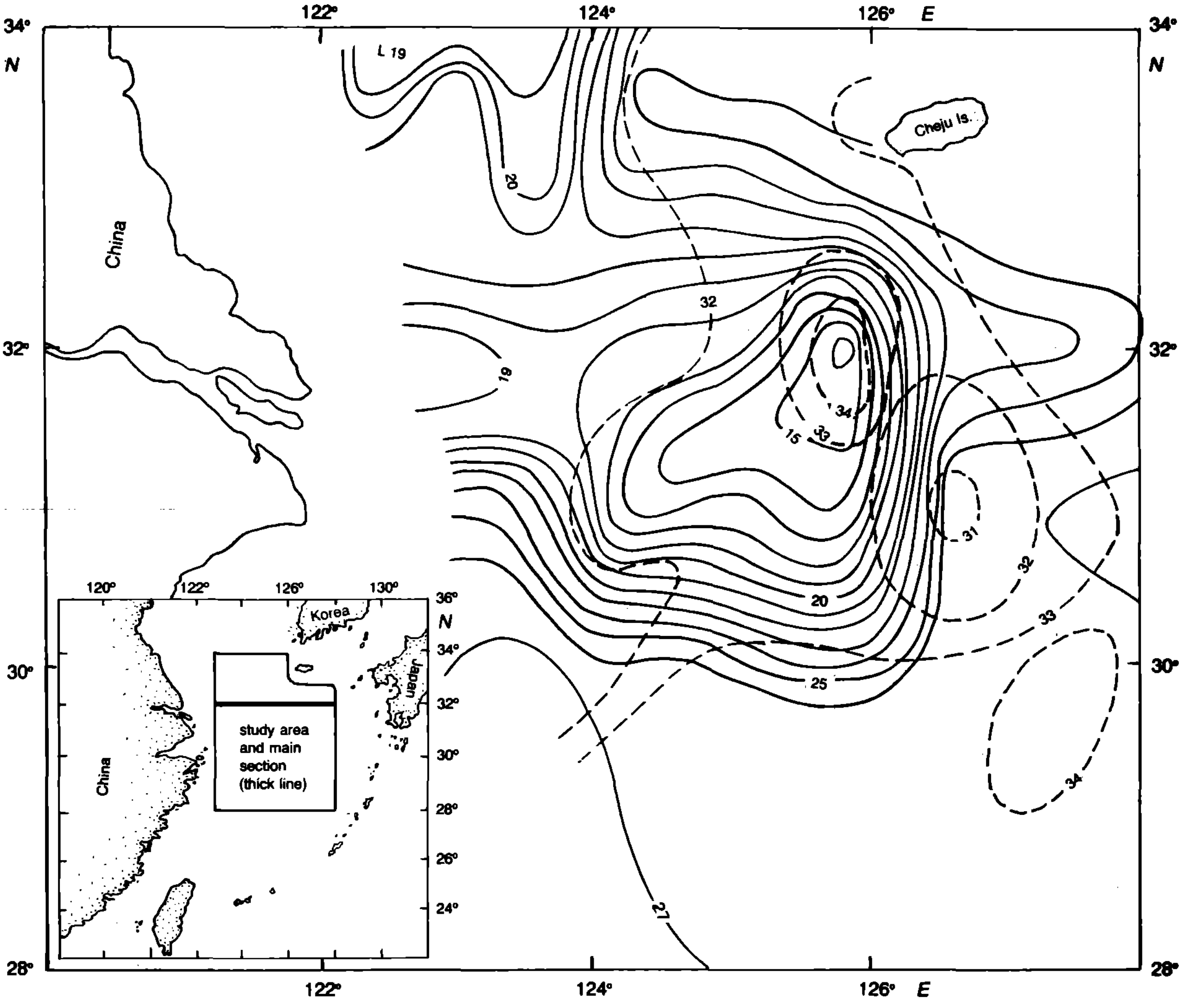
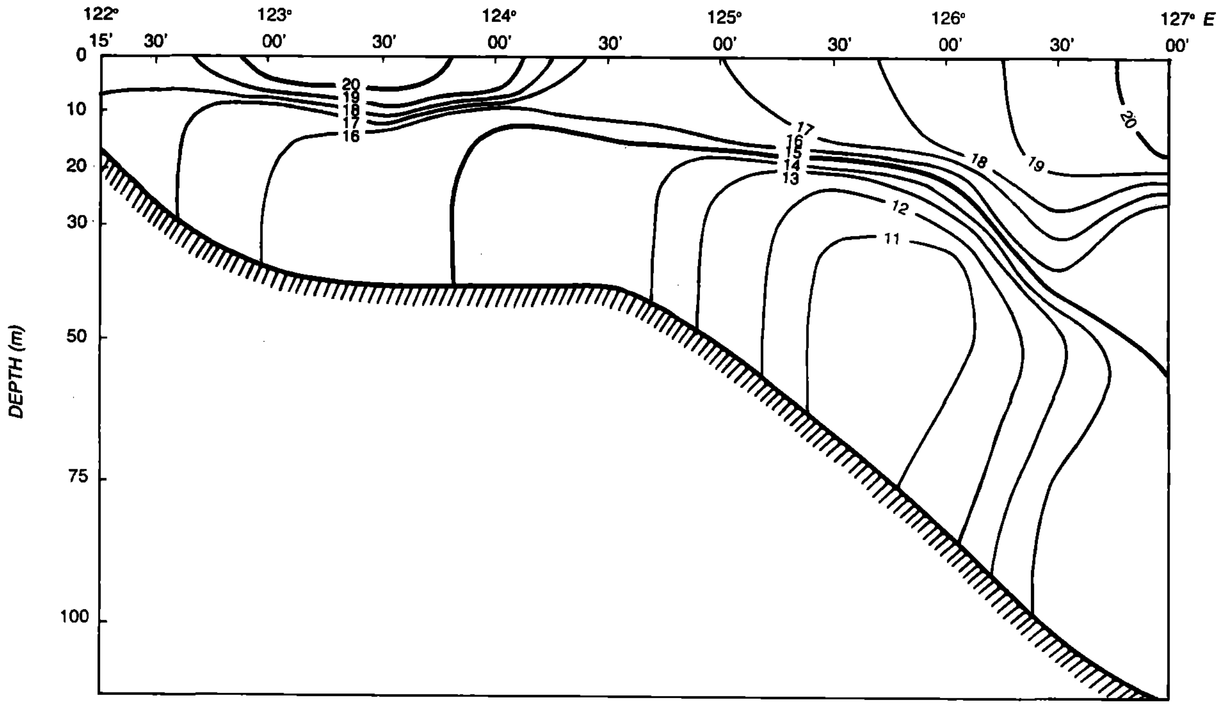
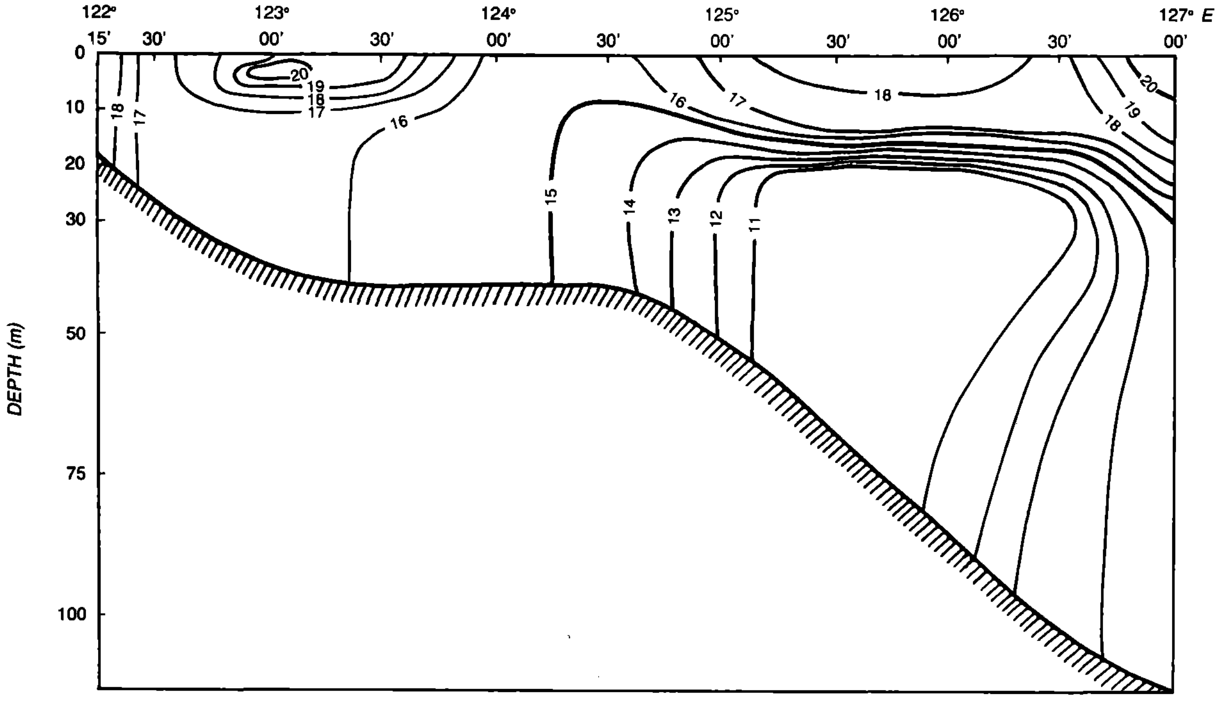


***Figure 1:** Distribution of temperature (°C) (solid line) and salinity (PTT) (dashed line) at 20m level in the eddy area, July-Aug. 1972.*

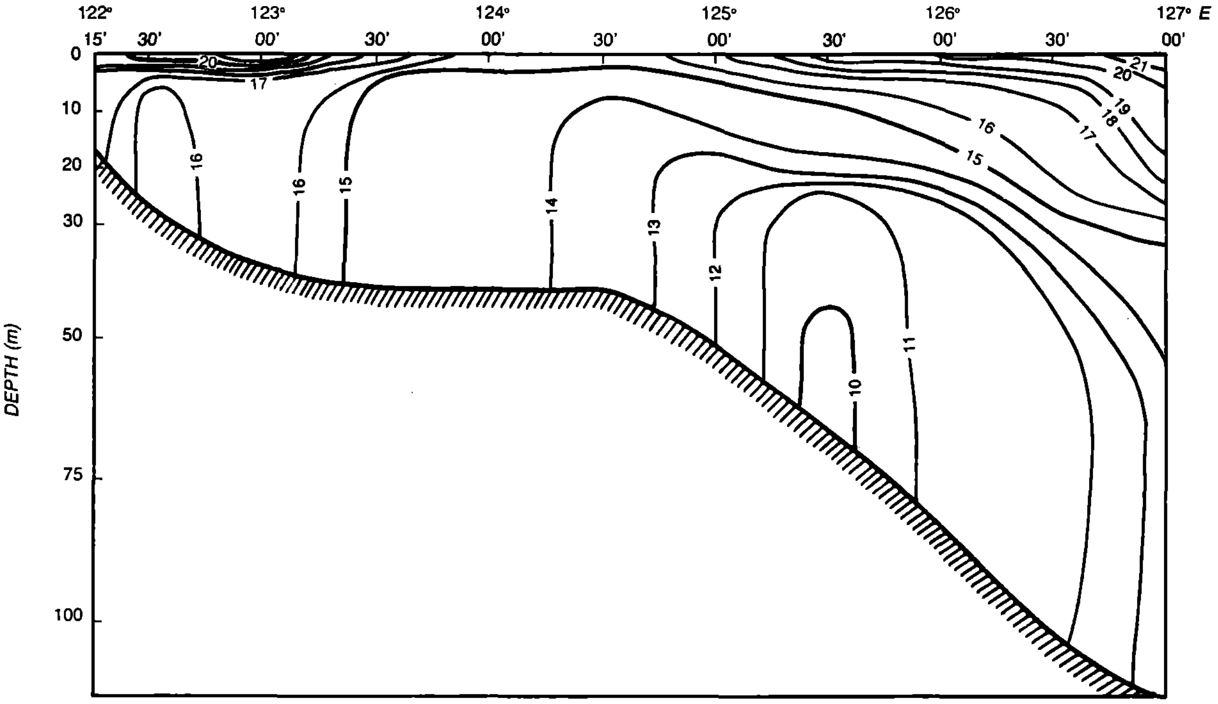
Figure 2: Thermal structure along 32°N in June from 1975 to 1984.



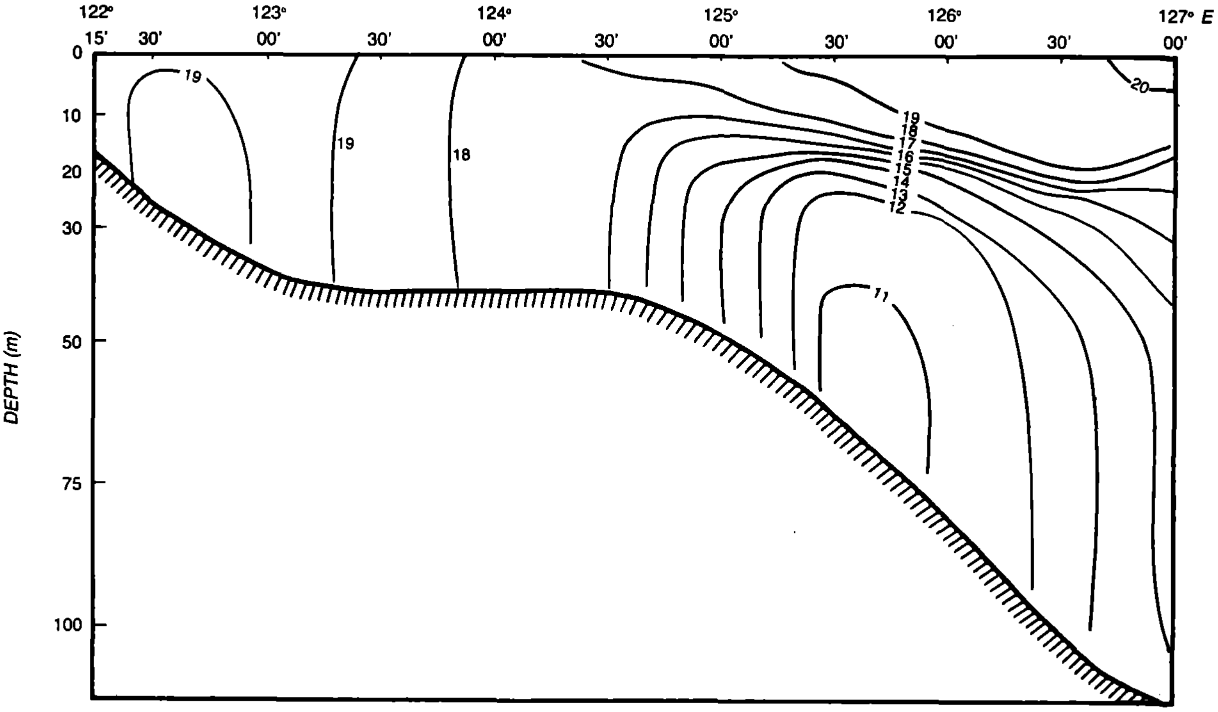
2a *June, 1975*



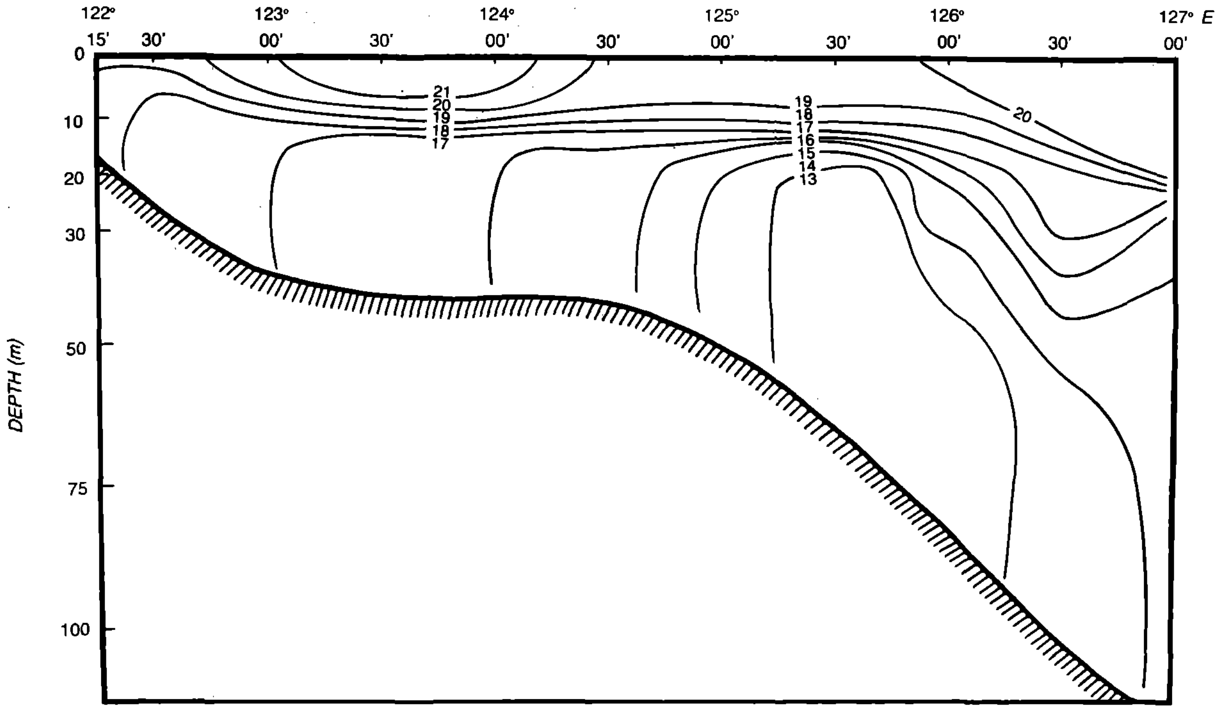
2b *June, 1976*



2c *June, 1977*



2d *June, 1978*



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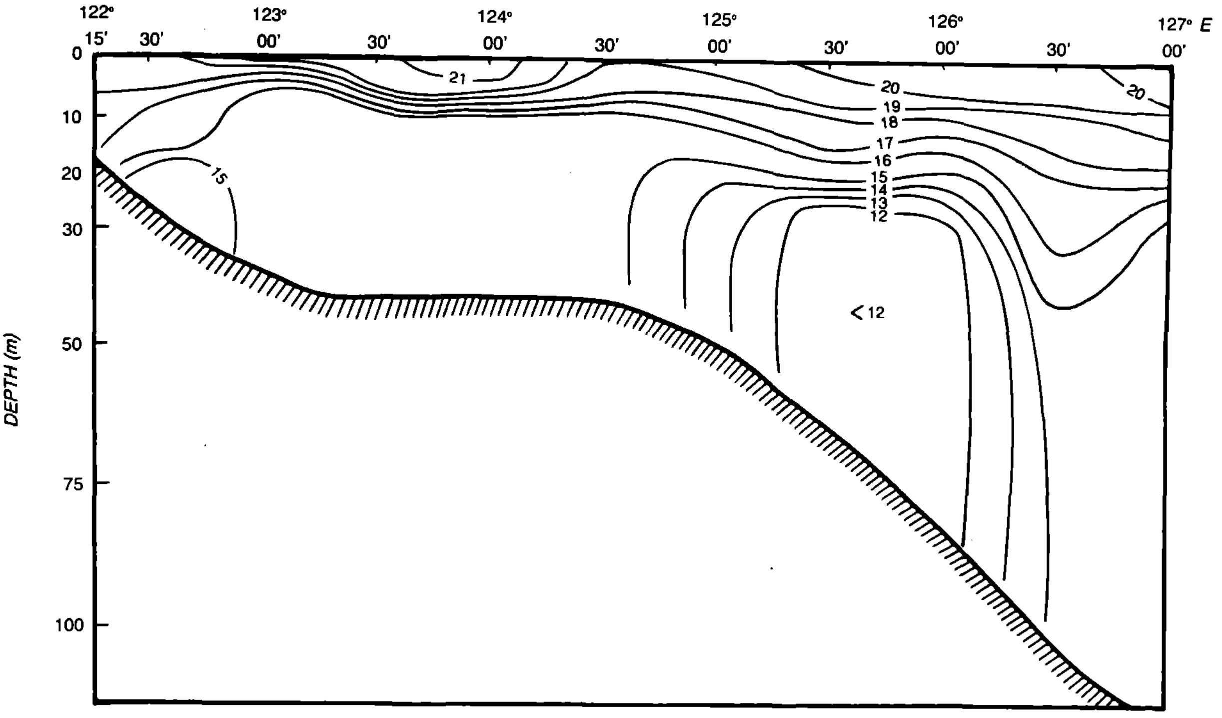
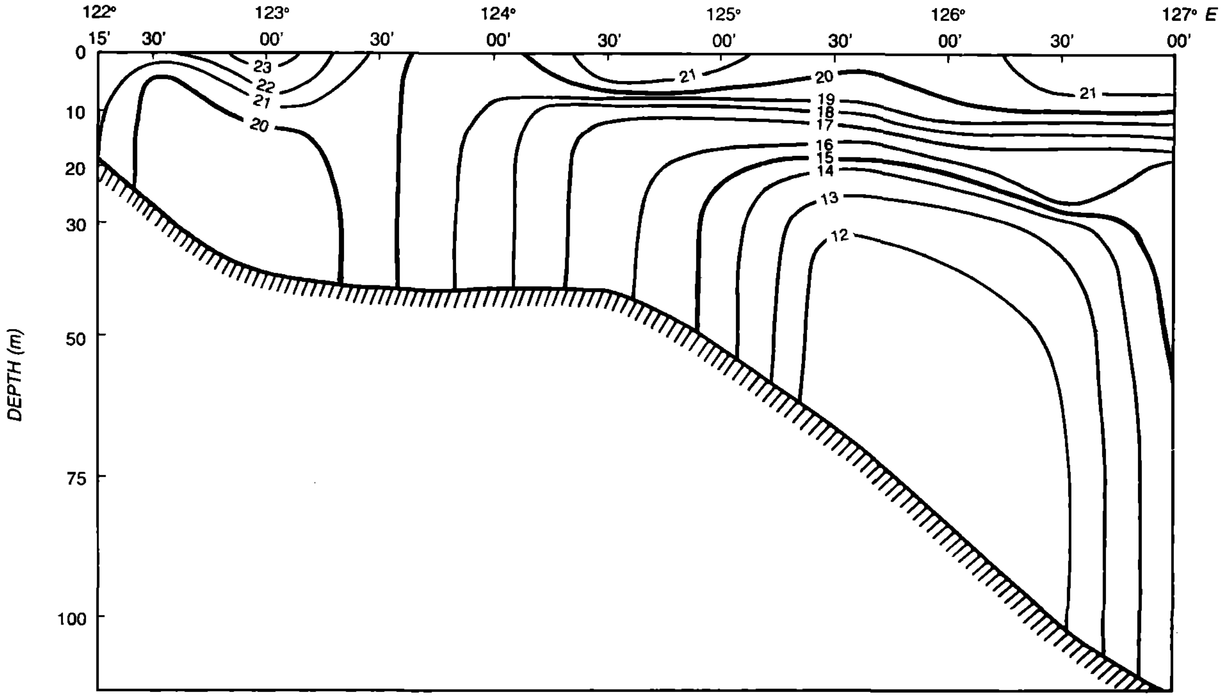
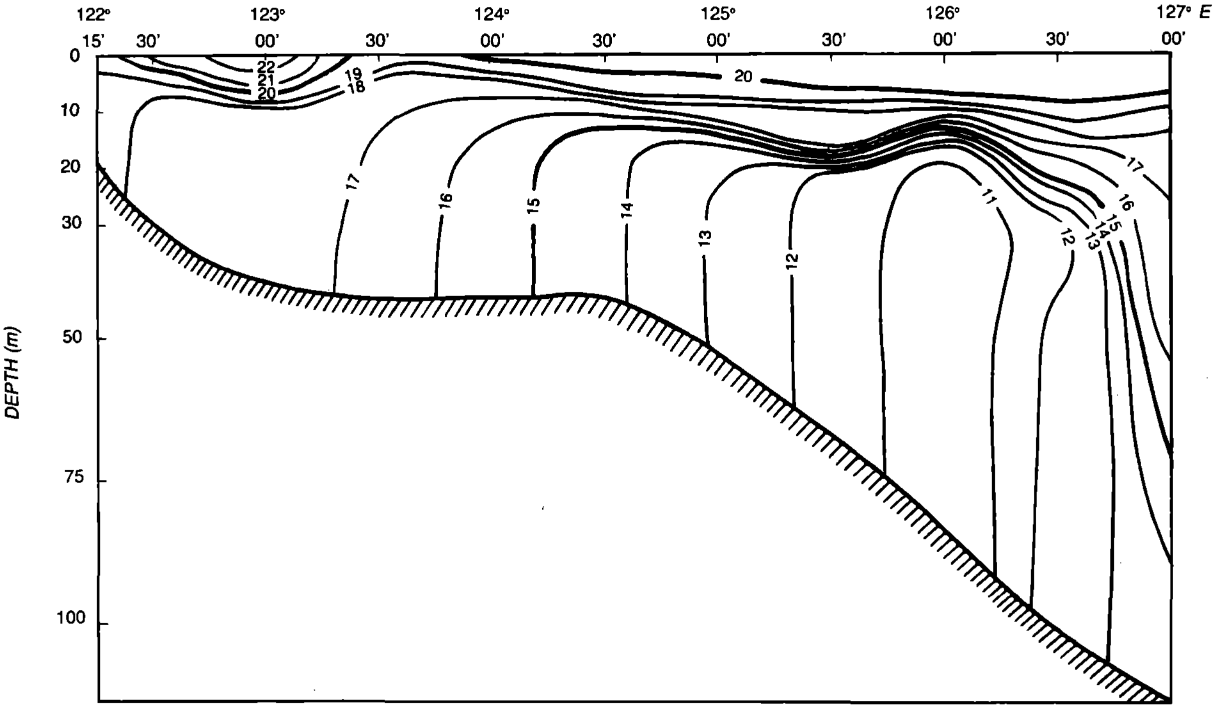


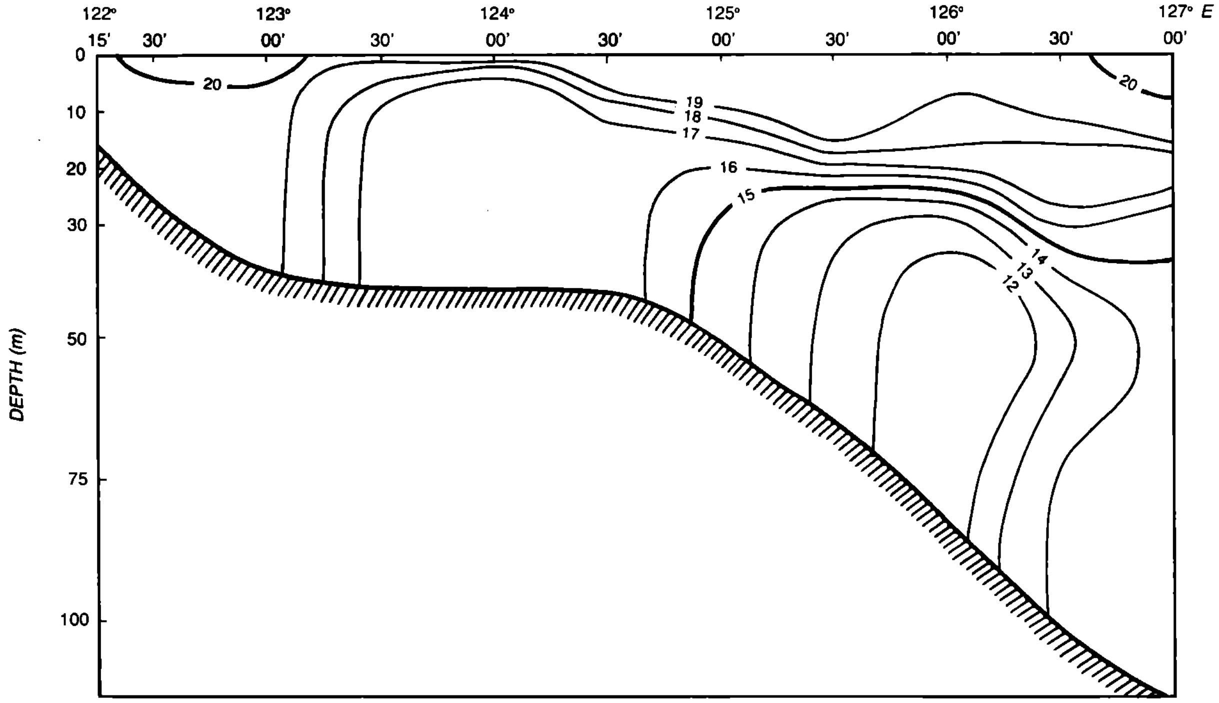
2f June, 1980



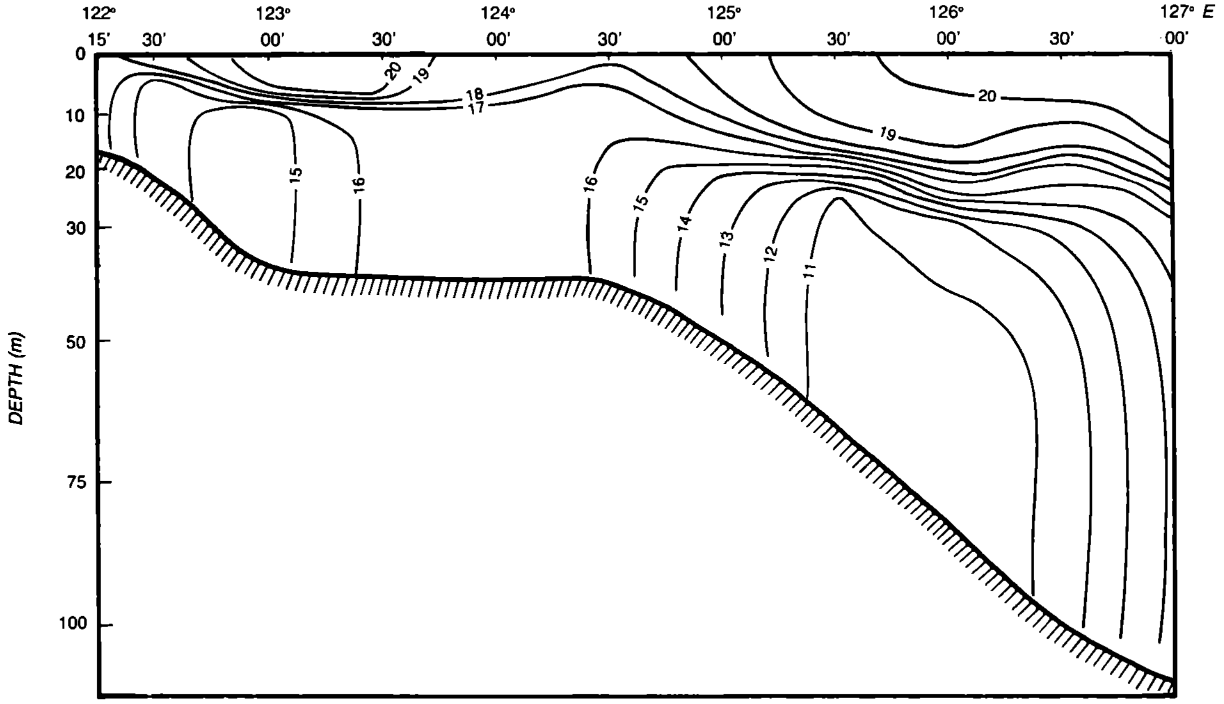
2g June, 1981



2h June, 1982



2i June, 1983



2j June, 1984

traditionally analyzed by others (Hu et al., 1980, 1984; Mao et al., 1983), and thereafter its association with El Nino events will be signified as was done by Hu (1984).

First of all, in order to show the relationship of the eddy to El Nino events, water temperature anomalies are obtained along a 32°N section at the 20 m level, i.e., the departures of in situ temperature near the eddy center from the sectional temperature mean at the 20 m level, to identify the eddy strength. Obviously, the stronger the eddy, the larger (in absolute value) the temperature anomaly. So the temperature anomaly is indicative of the eddy strength. However, in winter, water is so well mixed (vertically homogeneous) that the eddy cannot be discerned from the thermal structure, although the eddy is a year-round phenomenon (Mao et al., 1983). In this case, only the data from June of each year is used for analysis in Fig. 2 and Fig. 3. In Fig. 3, an index of El Nino (the curve of SST anomalies off Puerto Chicama, Peru) from Rasmusson (1984) is plotted for comparison. The stippled areas denote El Nino years, such as 1963, 1965, 1969, 1972, 1976, 1979 and 1982. It can be seen that all the El Nino years are accompanied with larger water temperature anomalies of the eddy than 3.2°C in absolute value, suggesting stronger eddy existence. In contrast with the above, the other areas enclosed by the curve and the abscissa -3.2°C-line denote non-El Nino years, all of which but two, 1978 and 1984, are accompanied with smaller temperature anomalies of the eddy than 3.2°C in absolute value, sugggesting weaker eddy existence. In summary, 4-6 months prior to El Nino events off South America, the eddy is stronger in June of El Nino years than in June of non-El Nino years. On this basis, one might conclude that a stronger eddy in the northern East China Sea can be considered as a harbinger of an El Nino. However, it should be noted again that there are two solid dots in Fig. 3, corresponding to non-El Nino years 1978 and 1984, and lying far above the -3.2°C-line, i.e., at -4.4°C and -3.9°C, which are inconsistent with this conclusion. A reason for this inconsistency can be plausibly argued as follows. As mentioned above, temperature anomalies are calculated at the 20 m level, where the thermocline is approximately located. Occasionally, internal waves take place. They might affect temperature anomalies. This might be the case for 1978 and 1984.

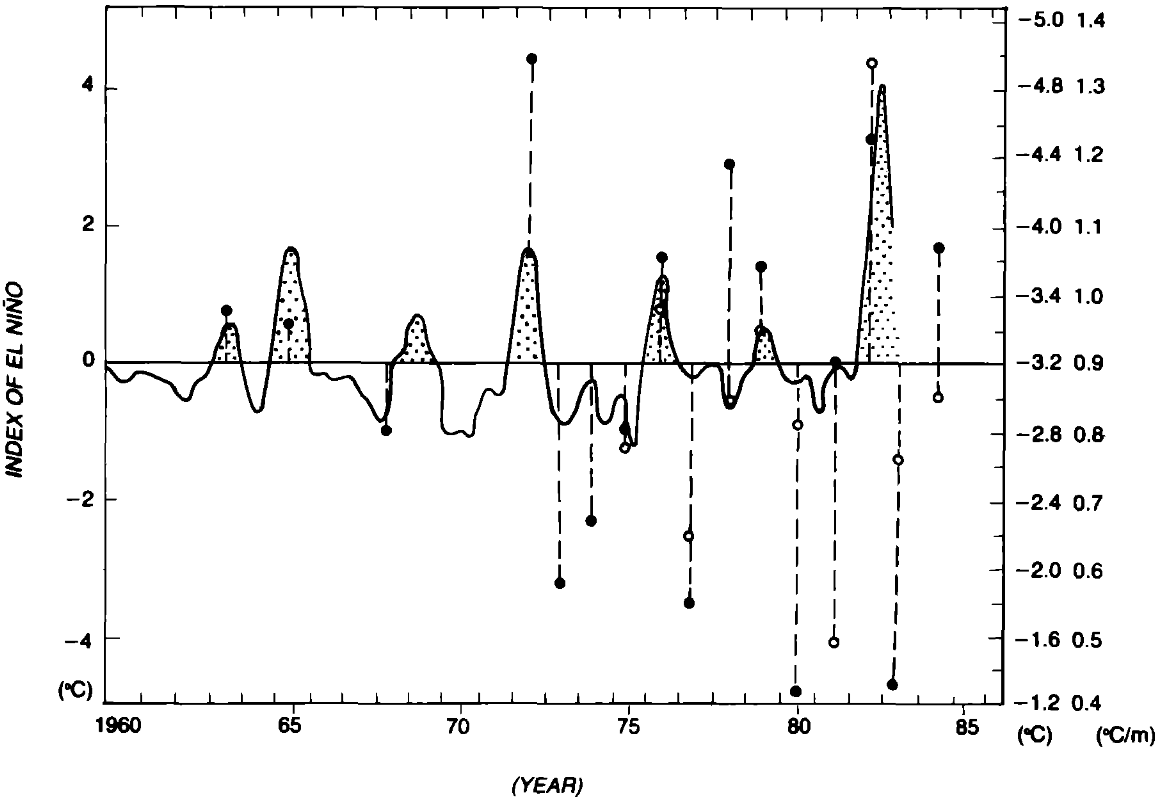


Figure 3: *Curve for an index of E1 Niño (Puerto Chicama, Peru, SST anomalies) redrawn from Rasmusson (1984), and eddy strength by temperature anomalies (°C, solid dots) at 20m in June and thermocline strength (°C/m, circled dots) near the eddy centre.*

With a view to eliminating the effect of internal waves, thermocline strength, as determined from 5m interval measurements, is also plotted. For the last two strong El Nino events (1976 and 1982), it can be deduced from Fig. 2 that the thermocline in June of both 1976 and 1982 was absolutely stronger than that of the preceeding and succeeding years. Furthermore, it is distinct as a whole in Fig. 3 that the interannual fluctuation of thermocline strength (open circles plotted in Fig. 3) near the eddy center is much more consistent with that of El Nino than are the temperature anomalies. This is not just fortuitous, for it is logical that a stronger eddy should result in a greater thermocline strength.

The question now is why the two phenomena are so well correlated. Without systematic measurements all the way from the western tropical Pacific Ocean up to the continental shelf of the East China Sea, only a simple hypothesis can be offered as follows.

As is well known, trade winds cause upwelling in the eastern tropical Pacific Ocean and warm water to be piled up in the west, forming a zonal sea surface slope, which tilts up towards the west. El Nino is generally considered the result of eastward propagating Kelvin waves resulting from the collapse of the "warming pool" or the sea surface slope in the western tropical Pacific when trade winds cease or reverse. Until Hu (1984) examined it, no one had paid attention to the influence of the collapse of the sea-surface slope on the circulation in the East China Sea and adjacent seas (except for the El Nino in the eastern tropical Pacific). Actually, there must be some kind of influence by a pre-El Nino change of the warming pool upon the western boundary current in the Philippine Sea and the East China Sea. Hu (1984) pointed out that the eddy was significantly affected or controlled by the Kuroshio and its branches, which are directly affected by the oceanic circulation in the Philippine Sea (and even in the western tropical Pacific). Thus, a study of the influence of the oceanic circulation including the western boundary current, upon the shelf circulation in the East China Sea will be important, not only for searching into the low frequency (interannual) fluctuation of the shelf circulation, but also for understanding the whole process involved in the large-scale, air-sea interaction and global climate change, and improving climate prediction.

In conclusion, consecutive measurements along 32^{O}N in the East China Sea are very valuable for both shelf circulation studies and air-sea interaction research. More routine survey lines in the Philippine Sea and the East China Sea, (like the 137^{O}E section occupied by the Japanese) would be of great value.

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4. Hydrostation "S" off Bermuda in 1984

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Thirty years of repeated oceanographic stations in the deep sea off Bermuda were completed in 1984. This report deals with the 1984 observations. A data report covering the full thirty years will be issued in early 1986.

Known as Station "S" (for Henry Stommel, who started the series in 1954), it is the only regularly reported deep station in the western North Atlantic and comprises the longest series of deep serial oceanographic stations in the world. Twenty-two stations were made in 1984, bringing the total to 554 -- roughly 18 or 19 per year or a little better than one every three weeks.

The station position is 32° 10' N, 64° 30' W, 20 km southeast of Bermuda in 3000 m depth (Figure 1). Since 1983 there have been quarterly stations further offshore at 32° 07' N, 64° 20' W in 4200 m depth. These stations were included to extend the time series into deeper water and to provide some idea of how representative Station "S" may be of locations further away from the island.

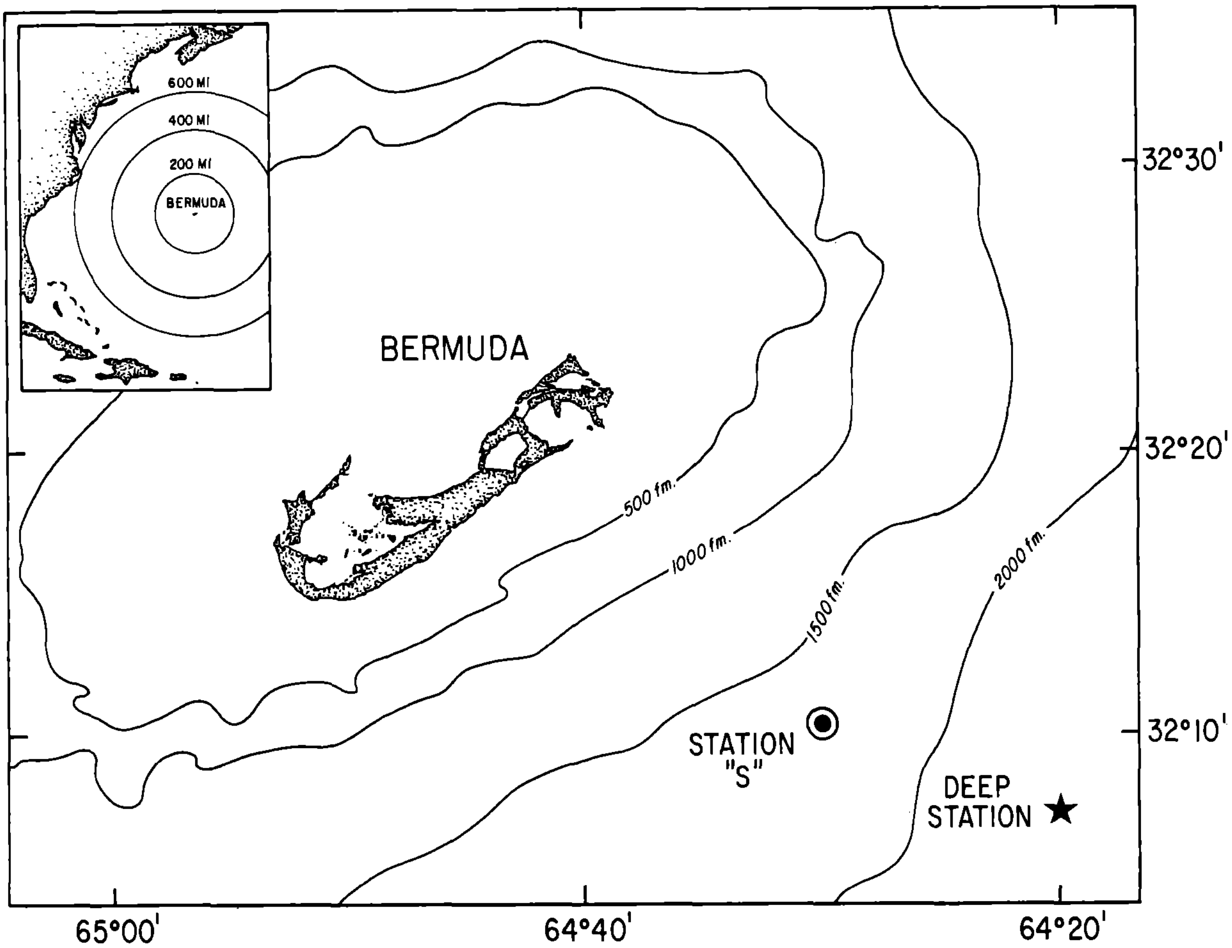

Figure 1. Location of Hydrostations off Bermuda

The deep stations are numbered consecutively with the regular stations. Beginning in 1983 the stations have been made from R/V WEATHERBIRD of the Bermuda Biological Station.

Each regular station consists of two casts with water bottles equipped with reversing thermometers. Temperatures and samples are obtained at 26 depths down to 2600 m. (At the deep stations there is a third cast, to 4000 m). Starting in 1983 the samples have been taken in Niskin bottles, usually of 5-liter capacity; Nansen bottles were used previously. Temperature (^{o}C), salinity (^{o}/00) and dissolved oxygen (ml/1) are reported routinely; measurements of nutrients, chlorophyll, primary production and other variables have been made from time to time. Since 1983 monthly measurements of nutrients, primary productivity and trace metals have been made in the euphotic zone, and occasional measurements of organochlorines have been made in surface waters.

Use of the larger Niskin bottles has also made it possible to provide samples for other investigators. In 1984 these included Dr. W. Jenkins of Woods Hole Oceanographic Institution for measurement of tritium, Dr. C. Measures of Massachussetts Institute of Technology for berylium, Dr. C. Keeling of Scripps Institution of Oceanography for carbon dioxide in surface waters, Dr. H. Pestana of Colby College for Sargassum spp., and Dr. W. Deuser of Woods Hole Oceanographic Institution for particulate matter.

The entire series is on file with the U.S. National Oceanographic Data Center and at Woods Hole Oceanographic Institution. Data reports through 1973 are available from the Bermuda Biological Station.

Temperature, salinity and oxygen data for 1954-1984 have been critically reviewed at Woods Hole Oceanographic Institution by R. Stanley, with advice from H. Stommel, H. Bryden, G. Knapp, M. Raymer and W.R. Wright and assistance from G. Heimerdinger of National Oceanographic Data Center. A data report will be issued in 1986 as a joint publication of the Woods Hole Oceanographic Institution and the Bermuda Biological Station. The report will list all data from the first 554 stations and is expected to include plots of temperature, salinity and dissolved oxygen versus depth for each station.

Eighteen stations were made at Station "S" between January 27 and November 30, 1984. Four additional deep stations were made in April, June, September and November.

The plot of temperature versus time for 1984 (Figure 2) is similar to those of previous years. The cooling trend in the upper layers noted in 1983 continued : the 20^{o} isotherm appeared in mid-May in 1984 compared with late April in 1983, and water warmer than 25^{o} was present for only three months (July-September) compared with nearly five (June-October) in 1983. However, the 18^{o} isotherm was somewhat deeper on average than in 1983. Cooling is barely noticeable in the thermocline (Table 1): the 15^{o} and 10^{o} isotherms were slightly shallower on average in 1984 than in both 1983 and the long-term means. There was also less fluctuation in the thermocline than in 1983, when some substantial displacements in the fall were attributed to Gulf Stream rings.

Because of very tight temperature-salinity correlation below the depth of seasonal influence, matching that of the Central North Atlantic Water (Wright and Worthington 1970), the salinity/time plot is not shown.

Three of the four deep stations were made within two days of a regular station. Deep station 540 (June 27) was about 0.5^{o} cooler than regular station 541 (June 28) in the upper 150 m but otherwise the two are identical. Regular station 547 (September 11) and deep station 548 (September 12 are identical at all depths. Deep station 553 (November 19) had good data only to 1500 m, and was cooler by about 0.5^{o} through the thermocline than regular station 552 (November 17). To date the regular stations seem fairly representative of conditions further away from Bermuda.

Acknowledgements

The Hydrostation "S" Series is supported by Grant No. OCE-8116410 from the U.S. National Science Foundation.

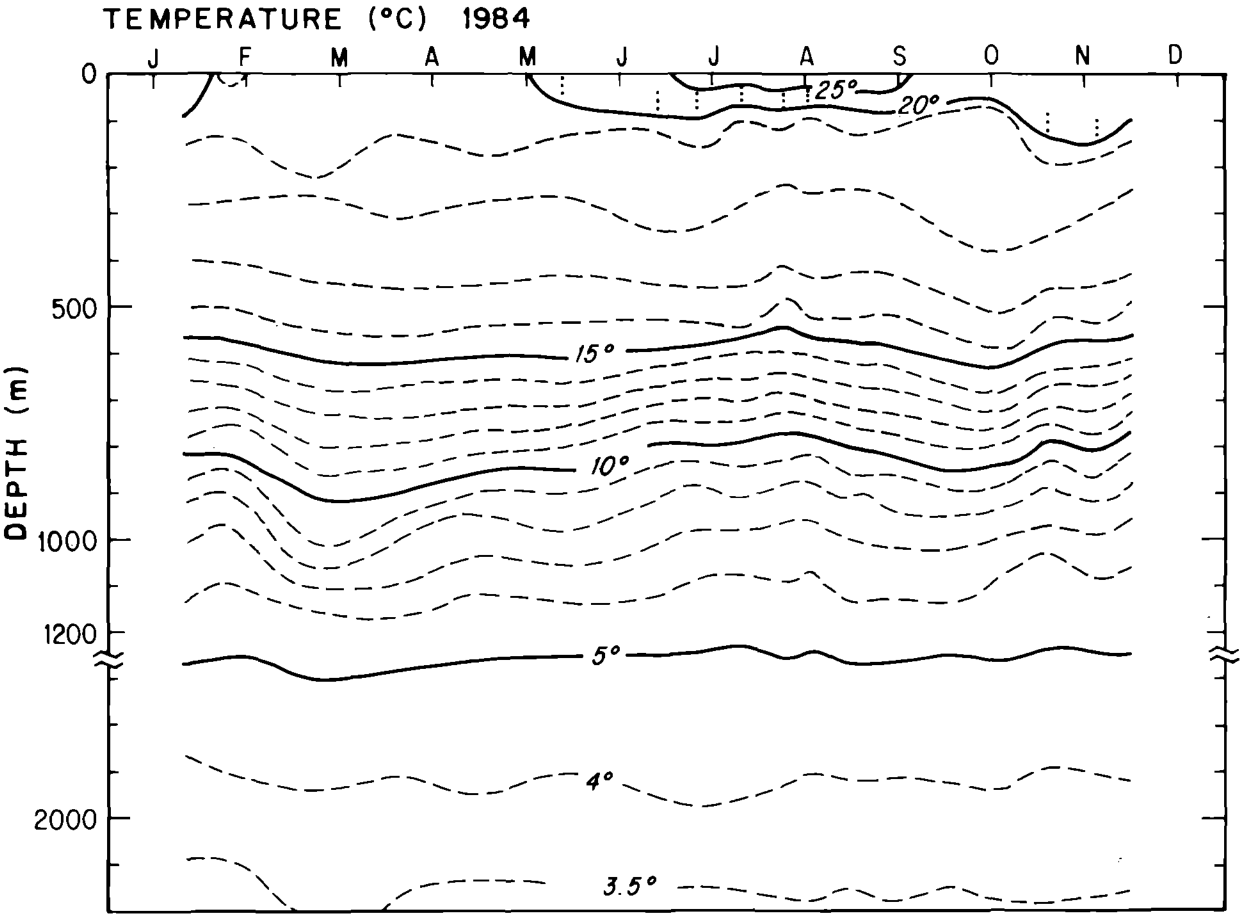

Figure 2. Temperature (°C) from Stations 533 through 554–(January-November 1984) plotted against time.

Table 1. *Mean Isotherm Depth (meters)*

Isotherm	1984	1983	1982	18-year mean
18°C	295	255	295	283
15°C	580	586	609	601
10°C	820	823	833	826
5°C	1315	1289	1253	1260

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Wright, W.R., and L.V. Worthington, 1970. The water masses of the North Atlantic Ocean; a volumetric census of temperature and salinity. Ser. Atlas mar. Envir. 19, 8 p, 7 plates.

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5. Temperature Time-Series Data Along the Coast of Senegal 1947-1983

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Senegalese waters are cooled by a strong coastal upwelling associated with northeasterly trade winds. This coastal upwelling is strongly linked with the dynamics of the canary current which is part of the North Atlantic tropical gyre. Sea surface temperature (SST) anomalies can get very large at times and directly influence the Senegal climate.

The Dakar Oceanographic Centre has been conducting a study of the interannual variability of this coastal upwelling since the early 60's. Nine coastal stations exist from Saint Louis north of Dakar to M'Bour to the south (see Fig. 1 and 2).

Surface temperature data at these nine coastal stations has been recorded for

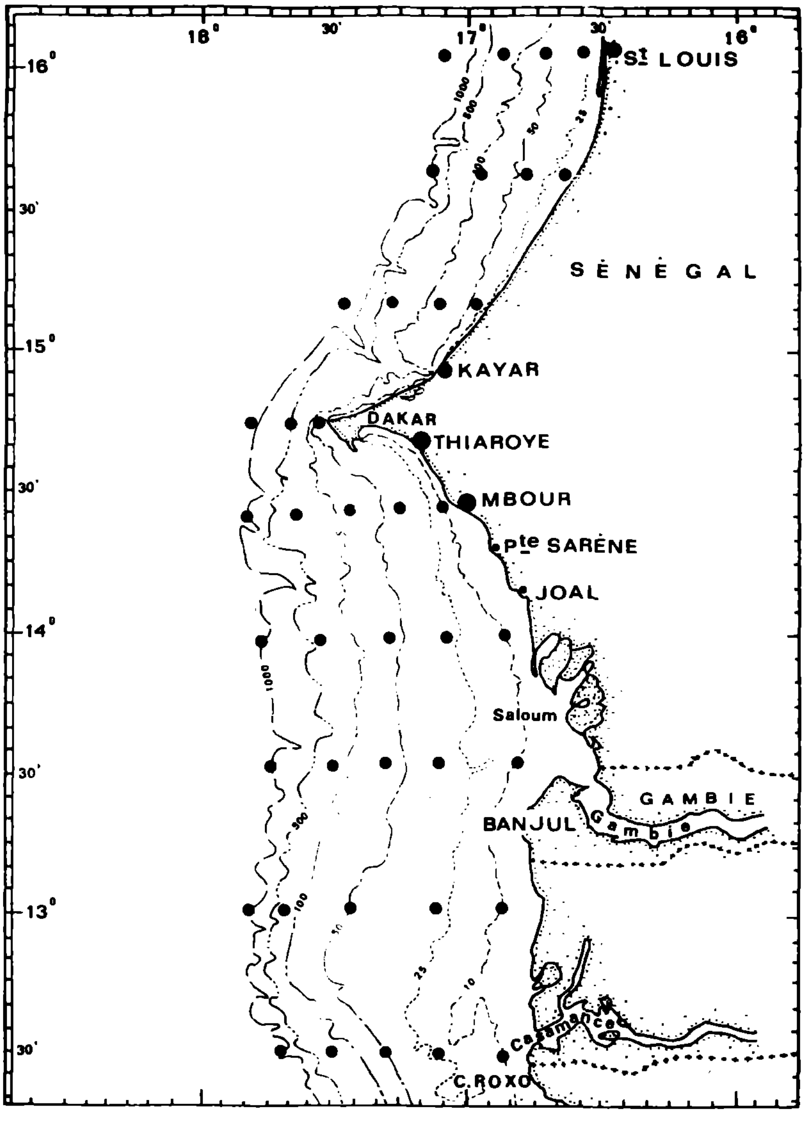


Figure 1. Location of coastal upwelling measuring stations.

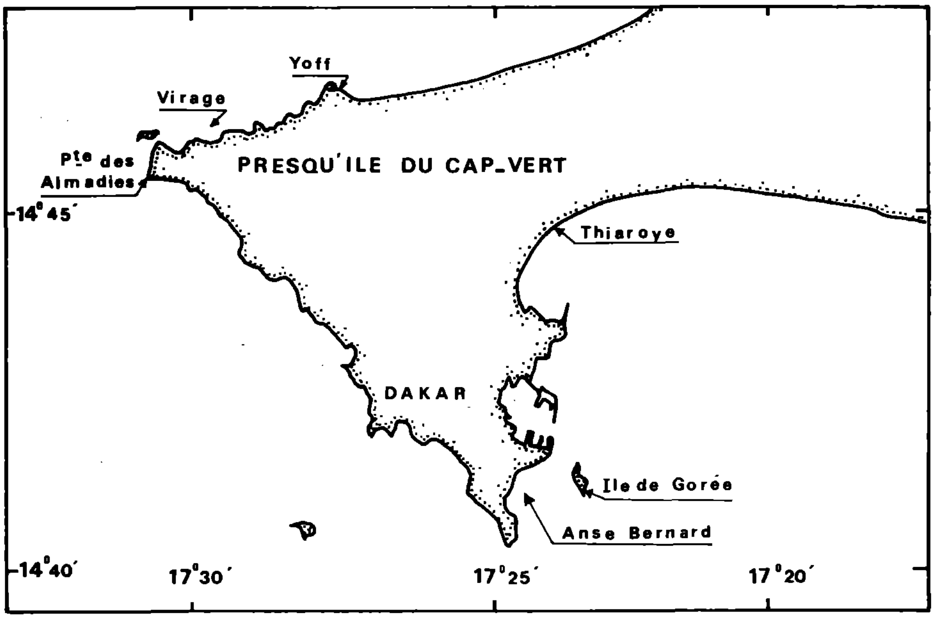


Figure 2. Location of surface temperature stations on the cape.

various intervals of time from 1947 to the present. At the time of the preparation of this publication, five of these stations were in service : Saint Louis, Kayar, Yoff, Thiaroye and M'Bour. The time intervals during which measurements were obtained (for the period 1947-1983) are shown in Fig. 3. The longest record is from M'Bour which runs from 1952 to the present. A complete compilation of this data by Roy et al (1985) is available from the Centre de Recherches Oceanographiques de Dakar-Thiaroye.

The sea surface temperatures along with daily anomalies are plotted year by year for each station on separate pages. Anomalies were obtained by taking the difference between the temperature of day (i) of the year being plotted and the average temperature of day (i). The latter were obtained by averaging all the temperatures recorded on day (i) for all the years during which measurements were made.

A visual inspection of the plotted curves allows the elimination of aberrant data. Among the stations still operating, those at M'Bour and Thiaroye seem to be the most reliable. Data from Kayar and St Louis seem to have a significant number of aberrant values during the period 1970-1975. In the following years, the reliability of these stations improved.

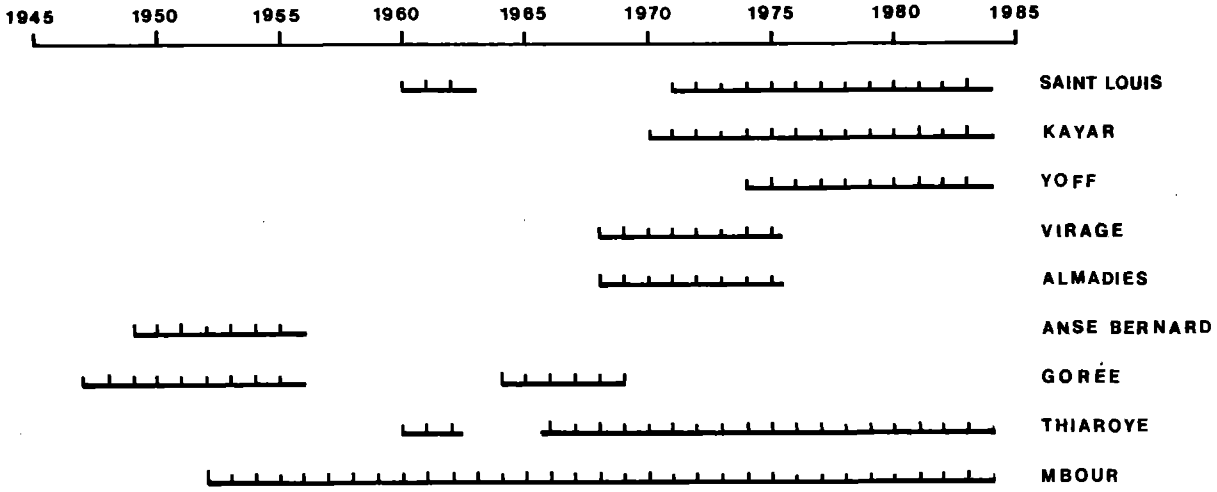
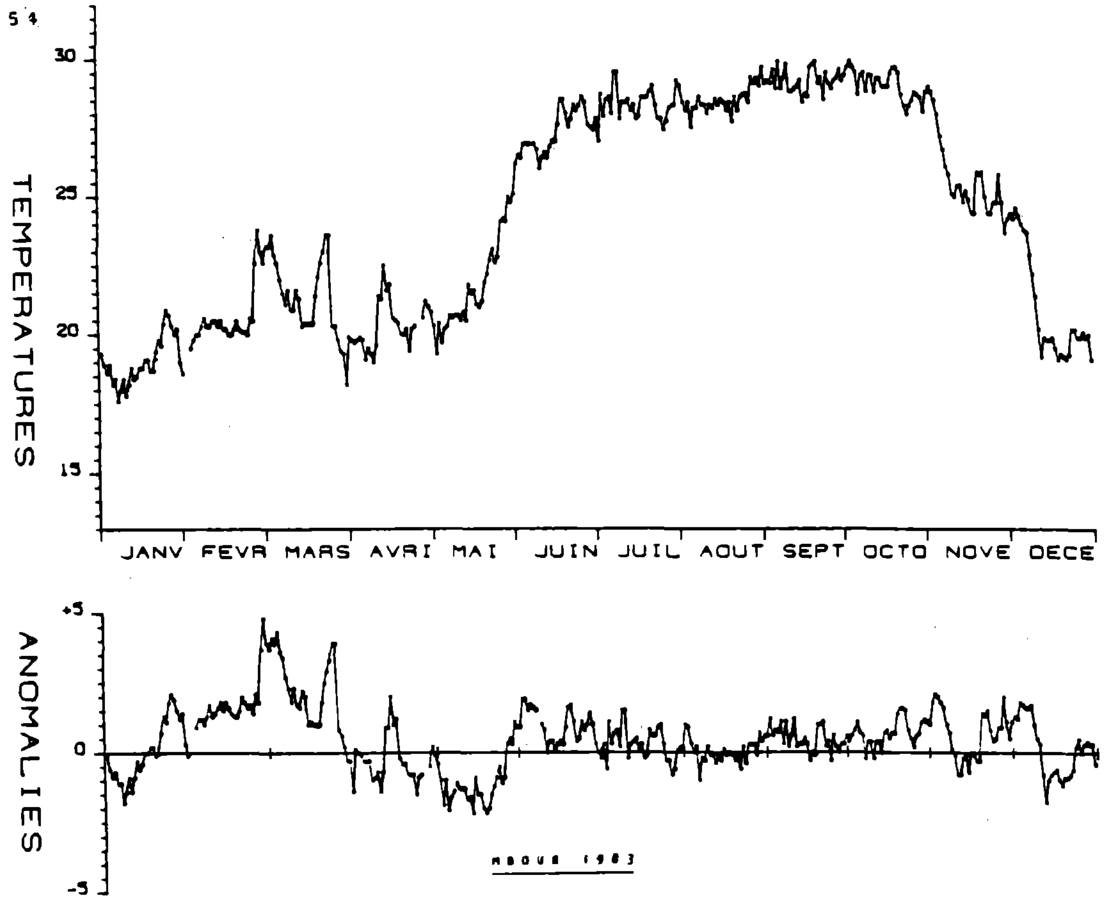


Figure 3. Time intervals when surface temperature stations were operational.

At the bottom of each page, two tables are presented. One contains the observed temperatures and calculated anomalies for each month. The second contains monthly averages of temperature and their anomalies along with the number of observations obtained during each month.

Examples of the observed temperature and computed anomalies curves of the 9-station data set are shown in Figs. 4-12. An example of the tables accompanying each of these curves is reproduced here for one of these stations in Fig. 4.



MBOUR 1983

JAN	193	189	186	189	182	184	176	180	184	178	182	188	184	185	188	186	191	191	187	187	194	198	196	204	209	207	203	200	202	190	186
	-1	-6	-9	-7	-11	-11	-18	-14	-9	-14	-9	-3	-6	-4	0	0	2	2	-1	0	7	13	11	18	21	19	15	12	14	3	-1
FEV	*	*	195	198	200	200	203	206	203	203	205	205	203	205	202	202	200	208	202	205	202	201	201	200	206	205	226	238	*	*	*
	*	*	9	12	12	10	13	17	13	14	16	18	15	18	16	14	13	13	15	20	18	16	17	14	21	18	37	48	*	*	*
MAR	230	226	232	232	236	229	226	220	215	211	216	209	209	216	213	203	204	208	208	204	214	224	226	230	236	238	203	203	198	194	193
	39	37	41	39	43	36	34	27	23	18	23	17	16	22	20	10	11	10	10	10	18	25	29	33	39	39	8	6	2	-3	-3
AVR	182	199	198	197	198	199	198	191	195	193	190	196	214	213	225	216	218	206	205	204	200	200	208	194	202	203	*	*	206	212	*
	-14	1	0	-1	-3	-3	-3	-10	-9	-7	-14	-7	9	9	20	10	12	-2	-4	-4	-8	-8	-8	-15	-9	-8	*	*	-5	2	*
MAI	210	208	203	193	204	197	202	203	207	206	207	207	205	208	205	218	215	216	211	210	212	219	222	227	231	226	220	241	242	241	250
	-1	-4	-10	-19	-10	-21	-16	-14	-11	-13	-13	-13	-17	-16	-22	-9	-15	-15	-20	-22	-20	-15	-12	-9	-5	-11	-9	3	5	3	11
JUIN	248	251	262	265	264	269	269	269	*	269	267	260	264	266	264	268	270	270	276	285	288	280	275	278	283	281	283	286	284	276	*
	9	9	19	19	15	17	16	15	*	10	8	0	4	4	1	3	4	3	9	16	17	11	4	5	11	8	10	19	10	3	*
JUIL	275	274	278	270	287	279	285	286	280	295	295	278	284	284	285	281	283	278	279	286	286	286	288	290	283	278	278	274	277	282	283
	0	-2	3	-6	11	3	7	8	2	15	15	-2	3	4	5	1	3	-2	-1	8	6	6	9	10	3	-3	-3	-8	-6	1	2
AOUT	283	292	290	284	281	284	275	282	282	286	283	283	280	283	282	285	283	285	284	281	284	277	286	281	286	287	287	284	293	291	293
	1	10	9	3	0	2	-10	-2	-3	2	-1	-1	-4	-1	-3	1	-1	0	-1	-3	-1	-6	2	-4	3	3	3	-1	7	4	6
SEP	290	297	291	292	291	296	289	299	289	293	298	288	288	289	290	292	288	287	286	297	298	299	291	293	285	295	291	289	292	293	*
	6	12	6	8	7	11	3	11	2	6	12	2	3	3	5	3	-3	0	-1	10	10	11	2	4	-3	6	2	0	3	3	*
OCT	296	292	294	297	299	297	295	287	294	295	288	294	294	288	293	293	290	290	290	295	297	297	295	287	283	280	283	285	288	287	286
	6	4	6	8	11	7	6	-2	4	4	-2	4	4	0	7	8	5	7	7	14	16	16	15	8	5	2	6	7	11	12	11
NOV	281	288	290	288	285	280	272	267	261	258	251	250	254	254	248	252	249	244	244	259	258	259	250	244	244	248	248	258	248	237	*
	10	18	21	20	18	16	10	7	1	-1	-8	-8	-2	-1	-7	0	-1	-3	-3	14	13	15	8	4	5	9	9	20	11	5	*
DEC	242	244	242	246	243	240	238	237	229	222	214	202	192	199	198	198	199	195	191	193	192	191	193	202	202	199	199	201	199	200	191
	11	13	12	18	17	16	16	17	10	5	3	-8	-18	-10	-8	-7	-6	-10	-12	-9	-9	-8	-6	2	5	0	3	4	3	3	-8

[illegible]

JAN	FEV	MARS	AVR	MAI	JUIN	JUIL	AOUT	SEP	OCT	NOV	DEC
190	204	219	202	219	271	282	284	291	291	258	210
0	17	21	-2	-10	9	2	0	4	7	6	1
31	26	31	28	31	29	31	31	30	31	30	31

Figure 4. Example of data from Mbour.

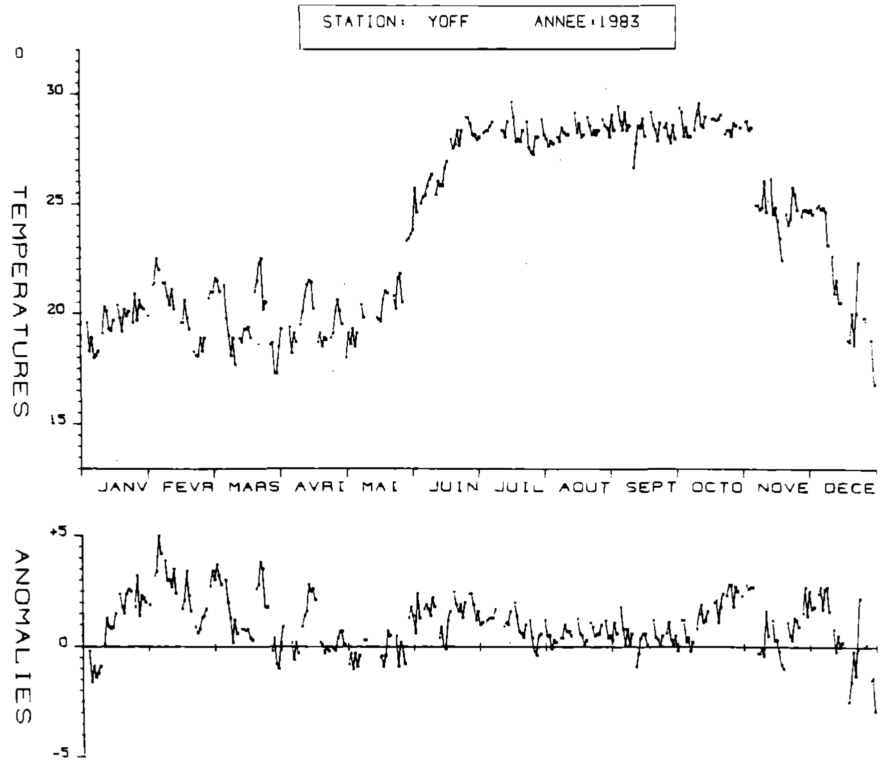


Figure 5. Example of data from Yoff.

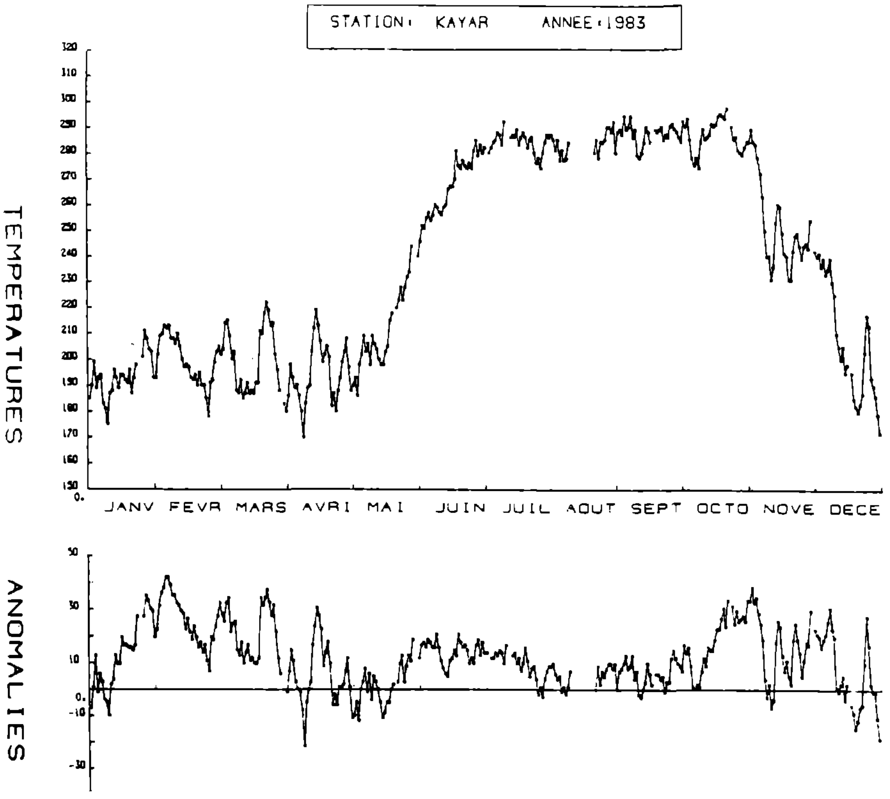


Figure 6. Example of data from Kayar.

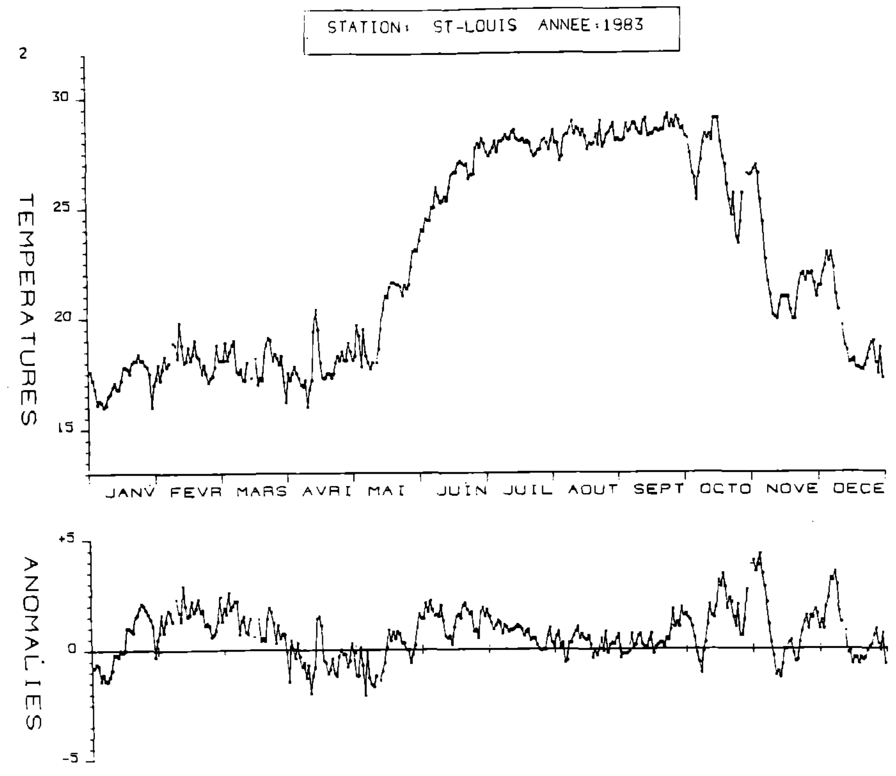


Figure 7. Example of data from St. Louis

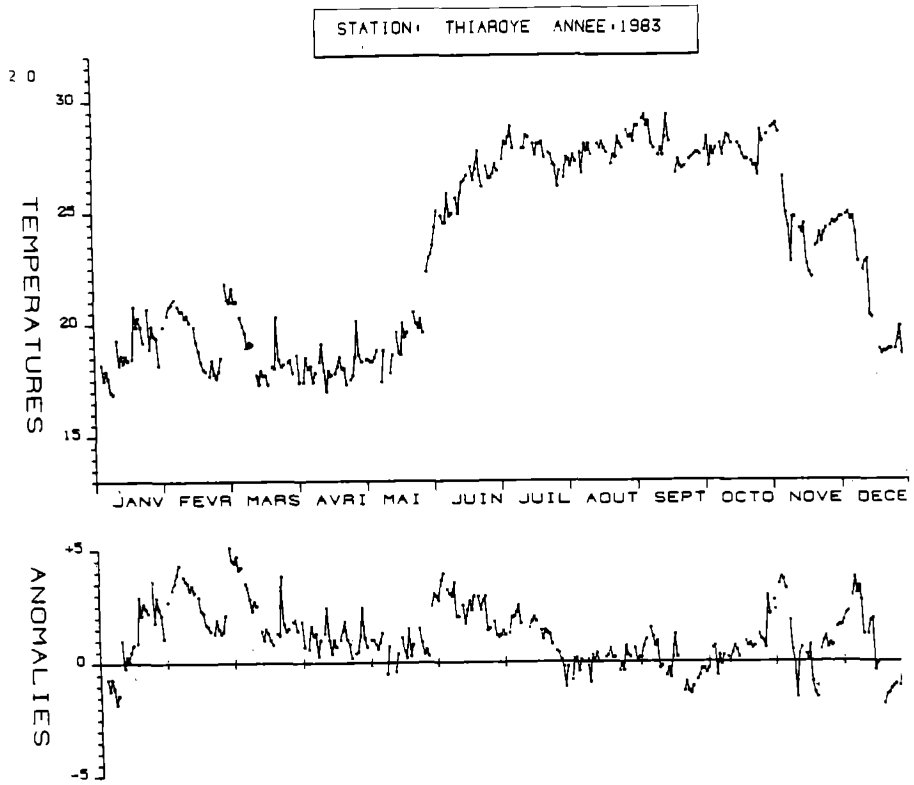


Figure 8. Example of data from Thiaroye.

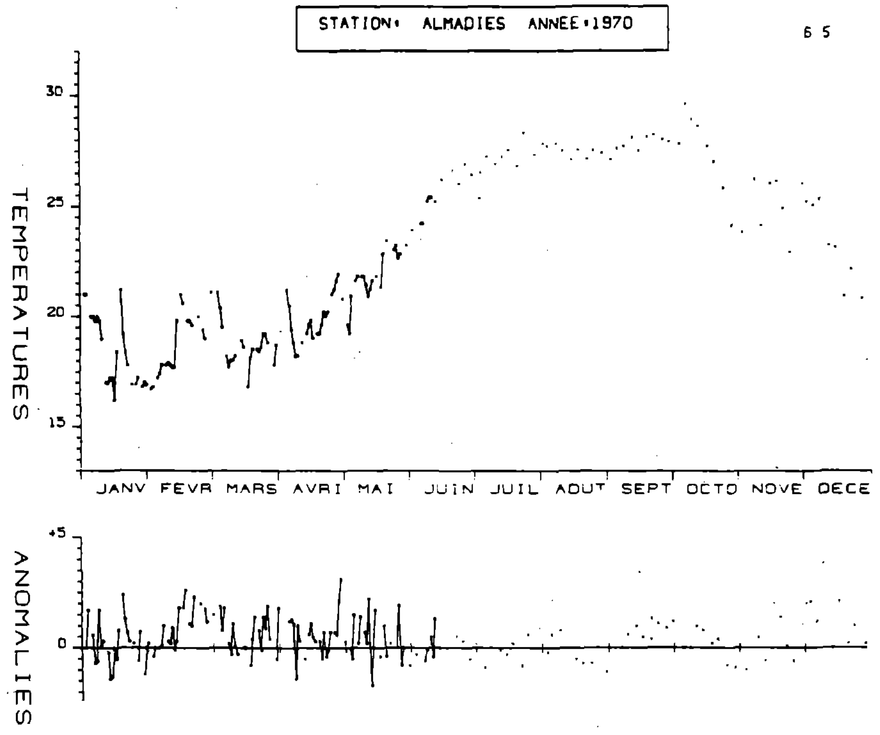


Figure 9. Example of data from Almadies.

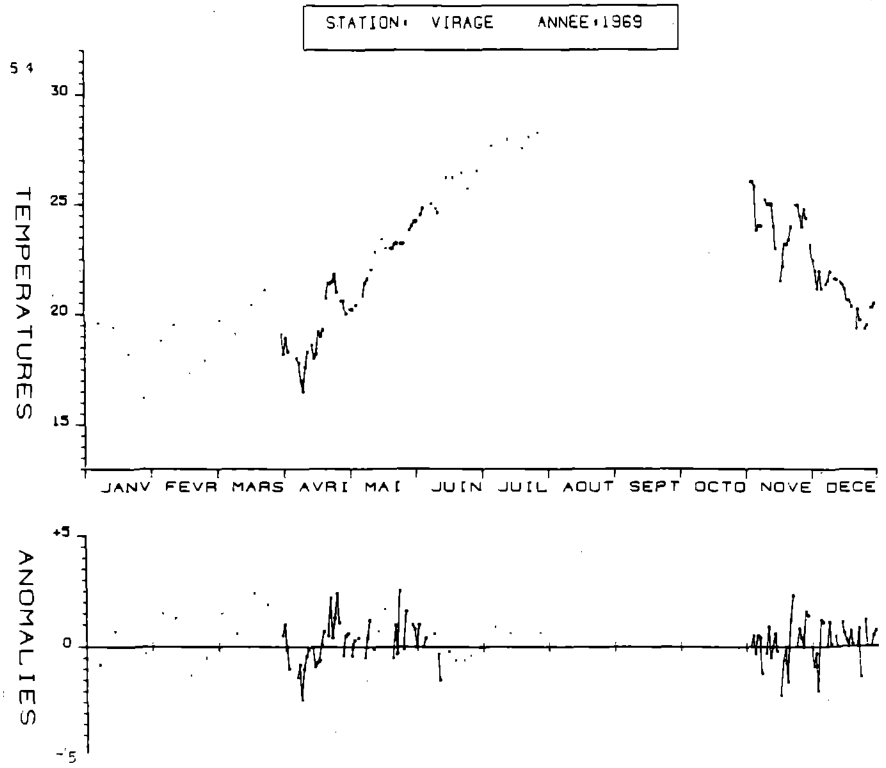


Figure 10. Example of data from Virage.

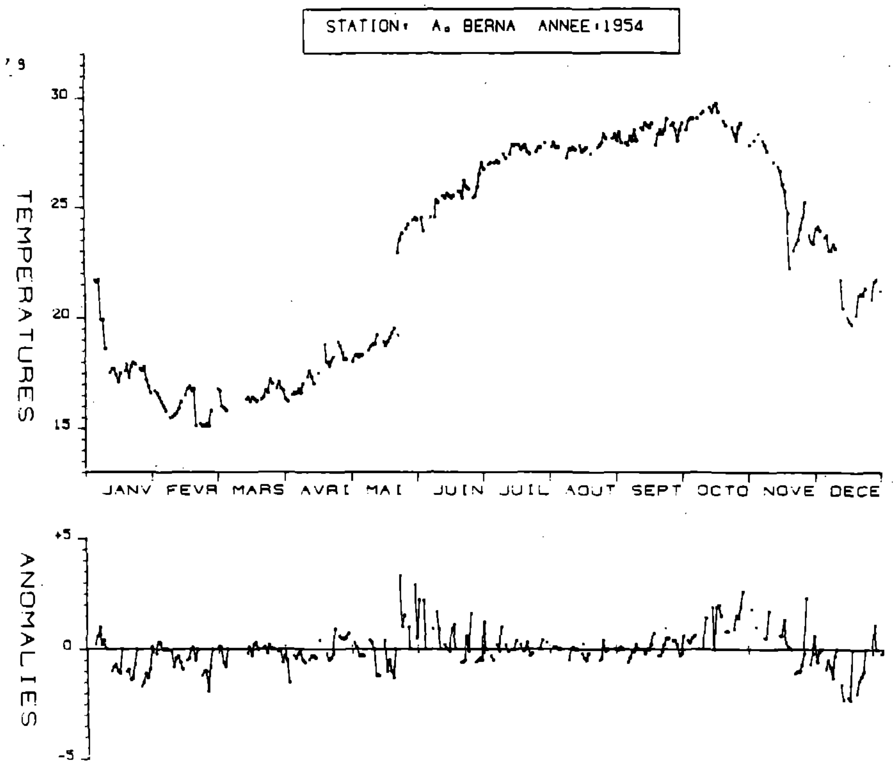


Figure 11. Example of data from Anse Bernard.

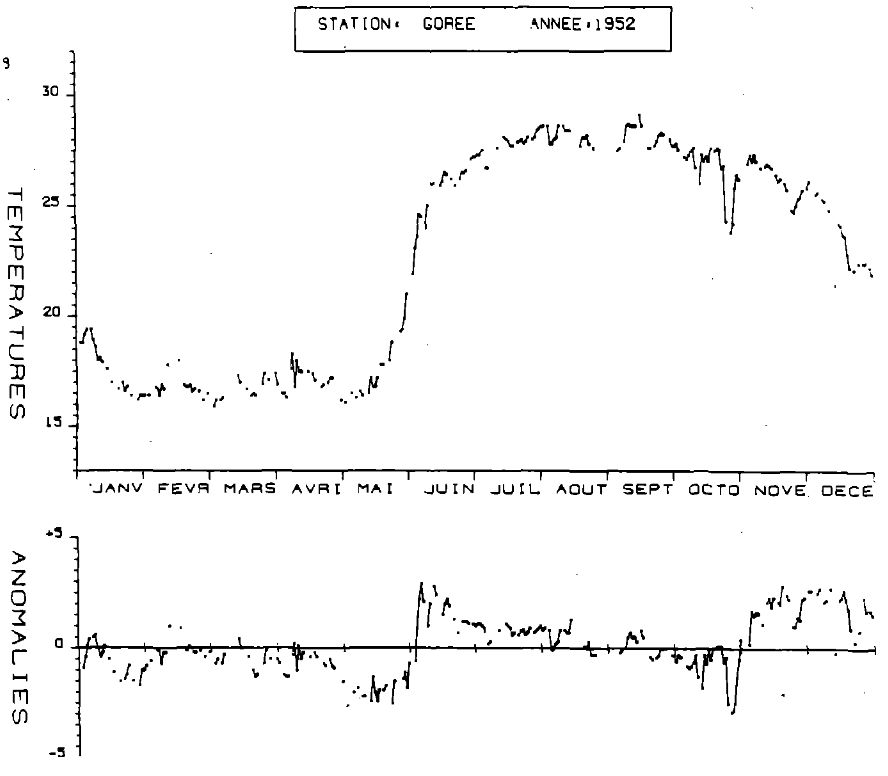


Figure 12. Example of data from Ile de Gorée.

In addition to this long term monitoring programme, shelf research has been carried out with a 24 m oceanographic vessel. The acquisition of a new 35 m oceanographic vessel is planned which will make it possible to occupy the hydrographic stations shown in Fig. 1 and thus reinforce the programme. The new vessel will permit better monitoring of the interannual variability of this major cold current as well as the associated meteorological parameters.

Moreover, in the months to come it will become possible to directly monitor and analyze the oceanic surface temperature field through satellite remote sensing. A reception station is hoped for in the near future. It will make possible a more detailed coverage of such parameters as SST and the position of the Intertropical Convergence Zone (ITCZ).

A tide gauge was positioned at Dakar and another one in the Cape Verde Islands for the FOCAL(1) experiment. These two gages are being maintained by the Centre.

A detailed analysis by Toure (1983) of the temperature field in the Bay of Goree is also available from the Centre. This document addresses the consequences of upwelling in the Bay on the development of the phytoplankton biomass.

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(1) FOCAL : Francais Ocean et Climat dans l'Atlantique Equatorial.

References

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Toure, D. 1983. Contribution a l'etude de l'"upwelling" de la Baie de Goree (Dakar-Senegal) et de ses consequences sur le developpement de la biomasse phytoplanctonique, Document Scientifique No 93, Decembre, Centre de Recherches Oceanographiques de Dakar-Thiaroye.