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REAL-TIME DETECTION OF FRONTS UTILISING IN VIVO PHYTOPLANKTON FLUORESCENCE PROPERTIES

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Real-time detection of fronts utilising *in vivo* phytoplankton fluorescence properties.

by

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Abstract

Historical data suggested that the monitoring of biological parameters might provide a real-time method of predicting the position of ocean fronts (critical to ASW operations).

A series of oceanographic surveys was therefore undertaken to investigate the distribution of various parameters (including chlorophyll *a* (Chl *a*), nutrients, ATP, and pH) across such fronts.

These surveys demonstrated that the continuous monitoring of chlorophyll fluorescence (Chl F) provided the most efficient real-time method for detecting the surface positions of deep-sea, shelf-sea, and shelf-edge fronts (often, in advance of temperature).

The *rate of change* in a parameter (not absolute levels) proved to be critical in detecting a frontal system.

A computer model was developed to flag alarms when the rate of change in a parameter indicated the proximity of the front. This was applied to a series of crossings of the Ushant front: at a rate of change of 10%, Chl F detected 100% of all crossings and skirtings of the front, 78% of detections being 0.5-2.0 miles in advance of temperature, with no false alarms. When the sensitivity was raised (5%), the distance advantage increased to 5.0 miles.

Seasonal baseline levels were established for Chl F around the UK. Changes in Chl F were also found to be associated with temperature and salinity gradients during the winter months. Chl F may therefore also possibly be used to detect permanent fronts throughout the year.

Attempts were made to refine the model by considering the effects of diurnal variation and the addition of the photosynthetic inhibitor 3-(3,4-dichlorophenyl)-1,1-dimethyl urea (DCMU) on the fluorescence: Chl *a* ratio. Diurnal varation was found to be masked by internal wave action, and the addition of DCMU was not found to enhance the correlation between Chl F and Chl *a*.

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NAW	North Atlantic water
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SECTION 1.

1. INTRODUCTION

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1. INTRODUCTION

1.1. Definition

Johannessen (1975) has defined a front in the ocean as "a zone where abrupt horizontal changes in the temperature and/or salinity fields takes place". Fronts are formed in every ocean, in surface as well as subsurface layers, and on scales varying from tens to hundreds of kilometers (Roden, 1974), and it has been estimated that frontal systems occupy nearly one quarter of the oceans' surface area (Johannessen, 1971).

1.2. Locations

Fronts are frequently found at the boundary between cold and warm water masses, at the boundary between coastal and oceanic water masses, around banks, reefs, shoals, island shelves, and along shelf edges, off estuaries, and along the margins of areas of upwelling.

Some major frontal zones are located over deep water with no correlation with bottom topography, while others correlate very well with the edge of the Continental Shelf (Simpson *et al.*, 1978; Johannessen *et al.*, 1978). Thus, whereas the position of some fronts can be predicted from the position of the slope (James, 1977), those in the open ocean are more difficult to predict. Models of tidal mixing processes have also been developed to predict the mean position of shelf sea fronts (Simpson & Hunter, 1974; Simpson *et.al.*, 1978; Pingree & Griffiths, 1978).

Unlike atmospheric fronts, major ocean fronts do not move rapidly but tend to remain within a fairly well-defined zone. Variability about this mean position, however, may be extreme and occurs in the forms of meanders and through the formation of warm and cold eddies (Barrett, 1971; Cheney, 1976; Cheney & Richardson, 1976; Fuglister, 1972; Gotthardt, 1974; Potocsky, 1973).

1.3. Importance

The characterization of frontal zones is important to an understanding of underwater sound propagation patterns, since these areas are marked by dramatic changes in layer depth, vertical temperature gradients and sound channels. These are all criteria which are important to ASW operations.

A well-defined class of fronts occurring in the shelf seas around the British Isles during the summer months marks the boundary between stratified and vertically-mixed regimes (Pingree & Griffiths, 1978). These seasonal fronts form a series of almost fixed geographical boundaries in the summer regime of the tidally energetic seas of the European shelf.

Evidence for the regular seasonal occurrence of one such front, the Islay Front, comes both from the historical temperature and salinity records and from satellite IR imagery (Simpson *et al.*, 1979). The structure of the Islay Front is akin to that of other shelf sea fronts in that it represents a transition from a

vertically mixed regime, where tidal and wind mixing predominate over the buoyancy input by surface heating, to a stratified regime where mixing is less important. It differs from other shelf sea fronts around the British Isles in that there is a large input of freshwater into the mixed coastal water resulting in the formation of a thermo-haline front, where the density gradients associated with temperature change are greatly enhanced by the salinity influence. Buoyancy input by salinity alone, which can produce haline fronts in coastal waters, does not apparently do so in this case, since there is no evidence for stratification occurring in winter (Simpson, Hughes & Morris, 1977).

Thus the transition from warm salty water to lower salinity cold water, which is generally considered to mark the boundary between Atlantic and Irish Sea water masses (Ellett, 1978), also marks the boundary between well-mixed and stratified waters where the major *vertical* density gradients in the stratified waters are determined by temperature rather than salinity differences, and the horizontal density gradient across the front is dominated by salinity (Pingree, Holligan & Mardell, 1978).

Where salinity is the dominating parameter for the density field in a frontal region, the acoustic front will be very weak or non-existent, due to the dominant effect of temperature on the speed of sound. However, ray-trace plots produced by the Admiralty Underwater Weapons Establishment (AUWE) miniserpent program using historical

data for the Islay front (Figures. 1-4) illustrate that the density gradient across the front can have a marked effect on sound propagation patterns, which is of consequence to ASW operations.

With a source (250Hz) at 4m in the mixed regime (Fig. 1) the effect of the front on sound propagation can be clearly seen. Although the source can be detected in the top metre of the stratified regime (in the west) at a considerable distance, the deflection of the sound waves by the density gradient results in an area of the stratified water not being insonified, hence the source cannot be detected. Similarly, if the source is placed at 33m in the mixed water (Fig. 2) the thermocline forms a boundary through which the waves reflected from the sea bed do not penetrate. With the source at 33m, however, it also cannot now be detected in the surface layer of the stratified water.

Using the same profile data, with the source at 4m on the west of the front (Fig. 3), no sound channel develops, and the source can be detected at any depth in the mixed or stratified waters. If the source is moved to 33m, (Fig. 4) the ray-trace pattern is again different, and the source can still be detected at any depth on the mixed side of the front. However, a surface layer develops to the west of the front, in the stratified water, where the sound waves do not penetrate, and consequently the source cannot be detected by any listening device in the upper stratified water.

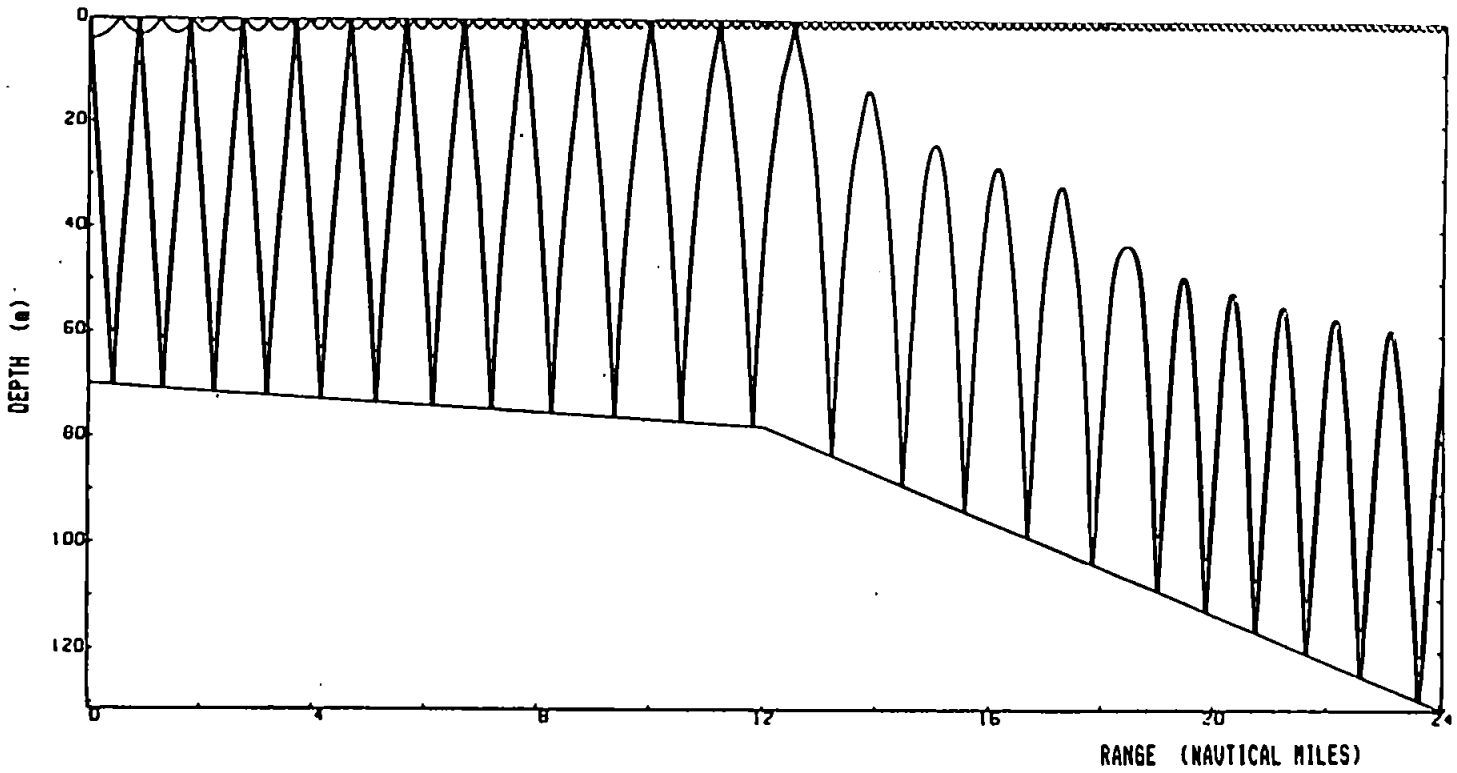

Figure 1.
Sound propagation pattern, Islay front (East-West).
Source at 4m in mixed regime.

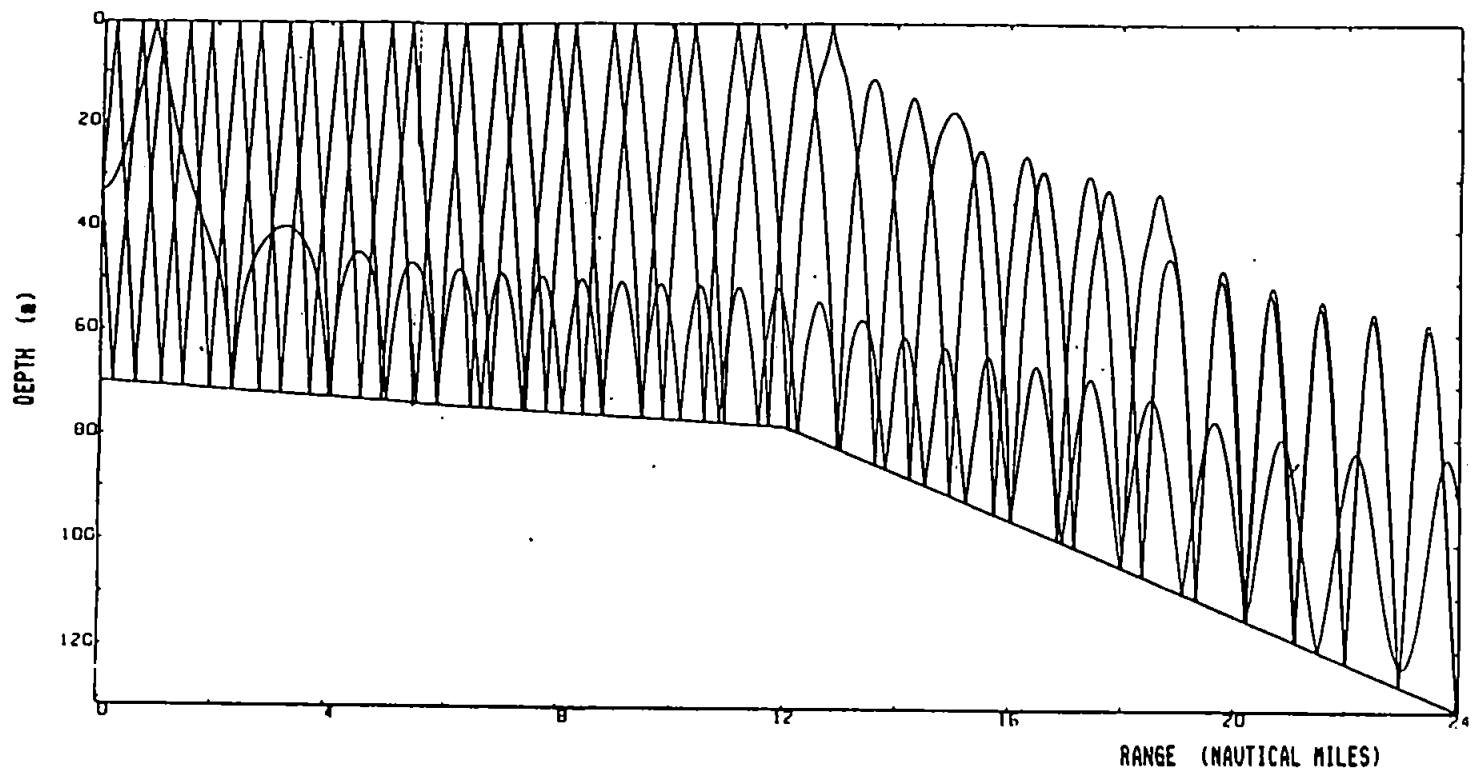

Figure 2.
Sound propagation pattern, Islay front (East-West).
Source at 33m in mixed regime.

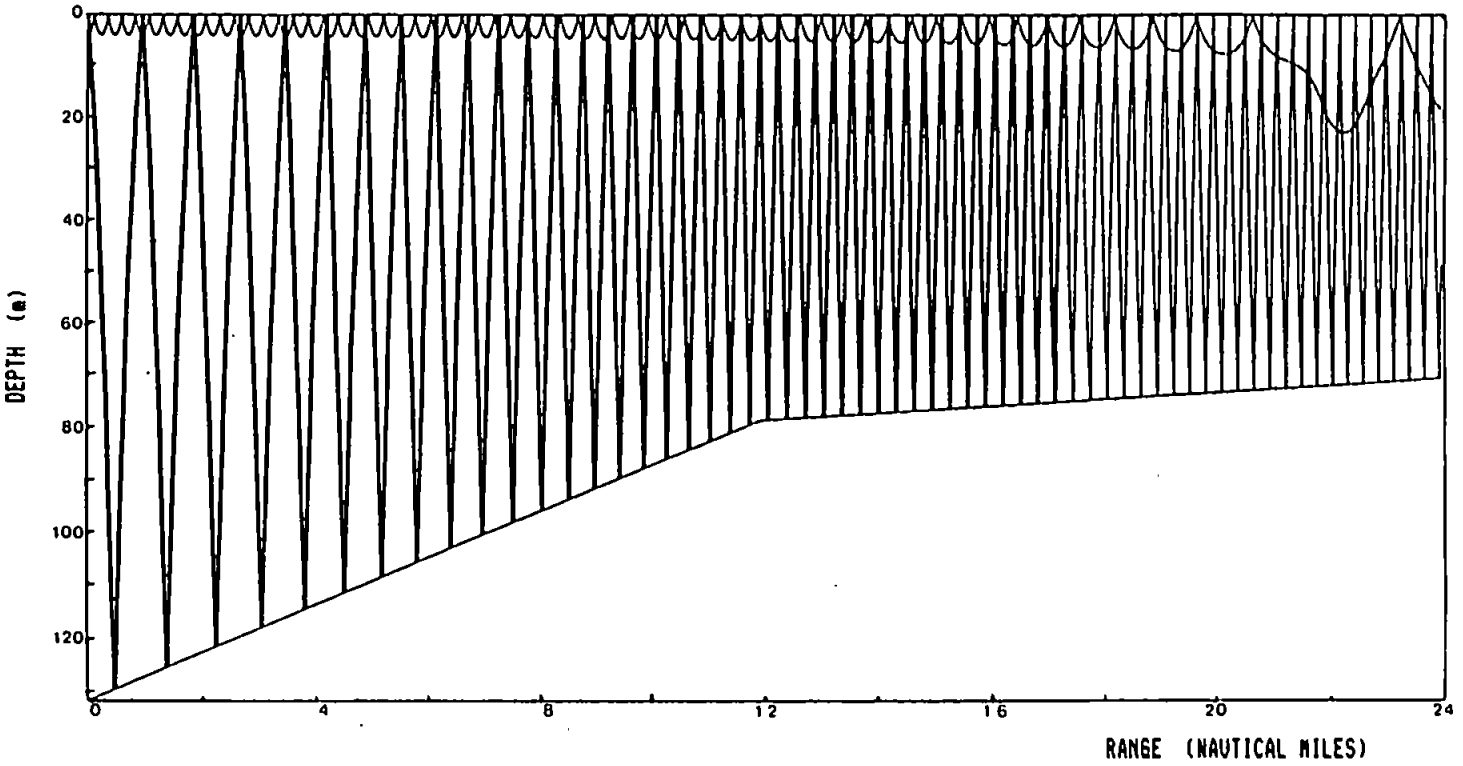

Figure 3.
Sound propagation pattern, Islay front (West-East).
Source at 4m in stratified regime.

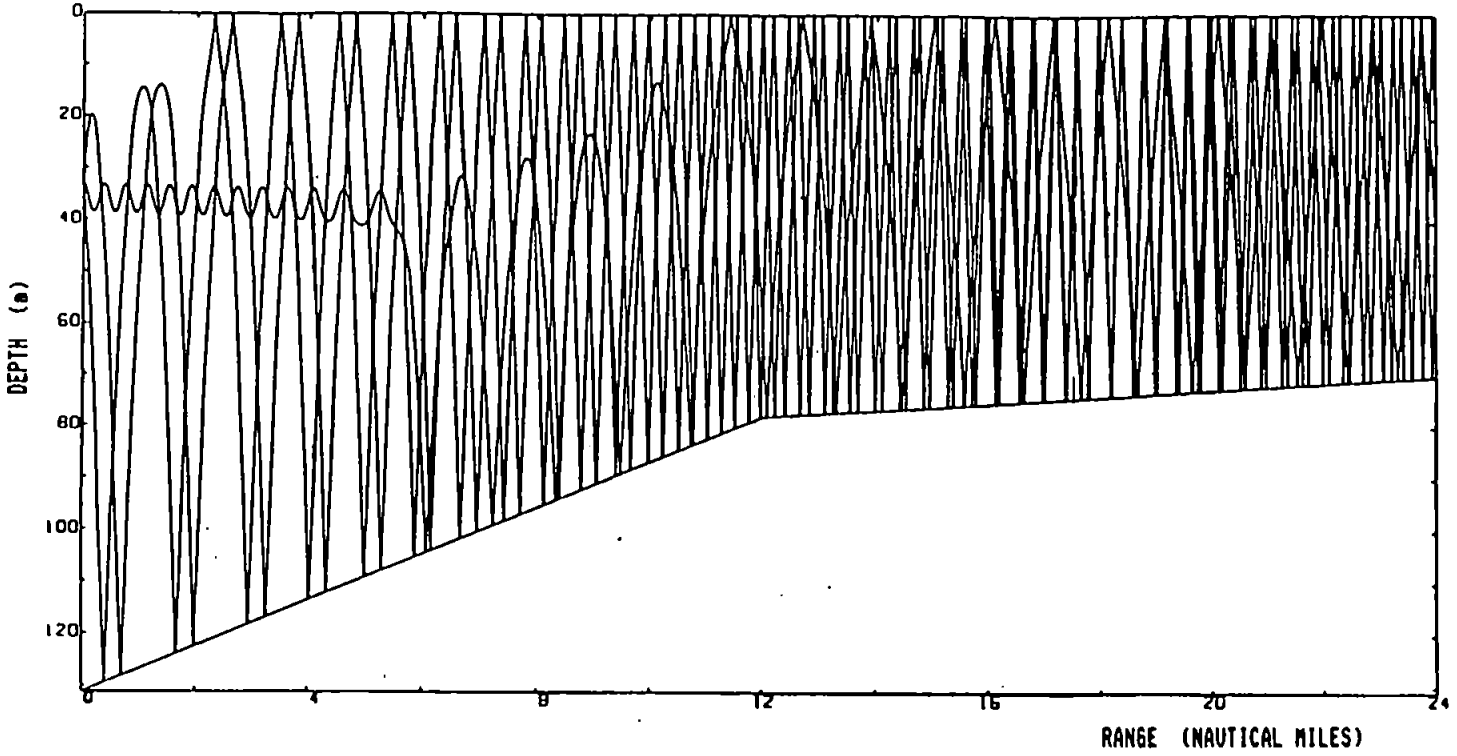

Figure 4.
Sound propagation pattern, Islay front (West-East).
Source at 33m in stratified regime.

The importance of these acoustic shadow areas to ASW operations is therefore obvious, and it is critical that the positions of such fronts are known as accurately as possible.

1.4. Detection

The most common approach to the mapping of ocean fronts and eddies is by the use of satellite data from infrared scanners. Such data can be utilized to derive information concerning sea surface temperature patterns (DeRyche & Rao, 1973; Legeckis, 1978). This method, however, has 3 main disadvantages:

1) infrared sensors respond to cloud radiation, sea mist and fog, as well as to that from the ocean's surface; thus if an area is completely cloud covered, thermal features cannot be identified. It has been estimated (Shenk & Salomonson, 1972) that approximately 40-50% of the Earth is obscured by clouds on any given day. However, the use of microwave temperature sensors which can penetrate cloud, but with a lower temporal and spatial resolution, could possibly overcome this problem;

2) satellites measure only the sea surface skin temperature pattern i.e. the top few millimetres, and therefore give no information on the subsurface temperature structure. In the case of cold eddies, which can lose their surface temperature characteristics in the first few months of their estimated two year lifetimes (Cheney & Richardson, 1976), satellite imagery would show

no anomalous thermal pattern although strong horizontal gradients exist below the surface;
3) it does not provide a real-time detection method, since although low resolution APT (automatic picture transmission) is now feasible onboard with the aid of small computers, this is can still only be obtained on cloud-free days.

In view of these problems, therefore, it would seem to be advantageous if another independent, but complementary, method of detecting/predicting the position of frontal systems could be developed for ASW applications using *in situ* methods (rather than remote sensing). A literature survey was therefore undertaken to investigate the possibility of using other physio-chemical or biological parameters in the detection of fronts. This clearly showed that, although the detailed structure within these fronts is complex, the basic pattern appears to be superimposed on the distribution of chemical nutrients, with important implications for the distribution of biomass. At the time this study was undertaken evidence had, therefore, accumulated which suggested that frontal zones may be biologically quite distinct from the adjacent water masses.

1.5. Fronts and Productivity

Frontal zones have been shown to correspond with sharp nutrient boundaries (Simpson & Hunter, 1974; Savidge,

1976). Selte (1955) presented evidence of high fish production in the North Pacific (34°N) in the region he referred to as the shear zone between the North Equatorial Current and the North Pacific Drift, and also in the region of large-scale semi-permanent eddies downstream from the Hawaiin Islands. In the North Atlantic, high productivity has also been reported at the front between the North Atlantic Current and the Irminger Sea (Steeman Nielsen, 1958) and over the Iceland-Faeroe Ridge where Hansen (1959) reported rates of production of 0.65-2.70 g carbon/m^2/day in contrast with the surrounding waters, where (in summer) the rate of production generally ranged between 0.15 and 0.25 g carbon/m^2/day.

It is perhaps surprising, therefore, in view of such productivity data and the accumulation of materials at the sea surface which has often been reported along fronts (e.g. Uda, 1938; Pingree *et al.*, 1974), that most of the earlier studies (Cromwell & Reid, 1956; Knauss, 1957; Voorhis & Hersey, 1964; Katz, 1969; Bang, 1973) were concerned with the physical description and dynamics of fronts, whilst their biological and chemical features received much less attention. This situation began to change in the mid-1970s with the shelf sea fronts around the British Isles beginning to attract investigation by several groups of workers (e.g. Pingree *et al.*, 1975; Simpson, Allen & Morris, 1978).

Savidge (1976) reported a band of high chlorophyll *a* concentration approximately 1 mile wide associated with a

surface temperature gradient across the Celtic Sea front (where the sharpest SST gradient covered about 2 miles). A similar seasonal chlorophyll maximum was also reported by Iversen *et al* (1979) along the Bering Sea shelf break front. Data presented by Simpson and Hunter (1974) and Savidge (1976) have demonstrated the existence of sharp nutrient boundaries correlated with sharp temperature gradients in the region of the summer thermal fronts in the Celtic and Irish Seas, which were more pronounced in the surface water than in the bottom water, as would be expected.

Aggregations of sound scattering animals often accumulate at the boundaries between waters of different properties (Hersey & Backus, 1963) and such aggregations have been used to map the boundaries which they mark. For instance, Frassetto, Backus & Hays (1963) were able to relate the distribution of sound scatterers to the distribution of Atlantic and Mediterranean water masses in the Strait of Gibraltar.

Greenlaw (1979) showed that acoustical estimates of zooplankton abundance can be made if the scattering behaviour as a function of the size and frequency for the zooplankters is known. The fundamental assumption of volume scattering is that the total scattered intensity from a volume containing a random distribution of scatterers is, on average, equal to the sum of the scattered intensities from each individual (McNaught, 1968 and 1969). One problem with this method is that the

volume scattering from a region containing one 22mm fish is equal to that from the same size region containing about 260 euphausiids, making the detection and estimation of euphausiids in the presence of fish difficult, although this problem could possibly be overcome by the use of multifrequency data. Another drawback to acoustical estimation is that, since the conversion of acoustical measurements to biomass relies on regression relationships between acoustical data and biomass from simultaneous net samples, the acoustical estimates contain all of the errors and biases of the net data (Kelley, 1976).

Despite these disadvantages, if such acoustical estimations were to prove feasible, the speed of acoustical sampling and the potential for obtaining high-resolution synoptic data over large areas suggests that this method might be of use in the detection of frontal systems. It would necessitate a detailed knowledge of the zooplankters likely to accumulate at a particular front, their pattern of diurnal migration, and the development of the relevant scattering models. However, since acoustic transmission is also very complex in frontal areas, this approach to detecting frontal systems would prove difficult.

1.6. Fluorescence, and factors affecting fluorescence.

The measurement of *in vivo* chlorophyll fluorescence as a method of estimating algal biomass (Lorenzen, 1966) is of particular interest to ecologists. However, the wide

variations in *in vivo* fluorescence:chlorophyll *a* ratios observed both in culture and in natural phytoplankton populations (Loftus, Subba Rao & Seliger, 1972; Blasco, 1973; Kiefer, 1973a,b) prevent this method being used in the determination of absolute concentrations of chlorophyll *a*, which itself is only one aspect of the biomass.

In vivo fluorescence is essentially excitation left over after the demands of photosynthesis have been satiated, and is almost entirely due to excitation passed on from the light-harvesting pigments to particular chlorophyll *a* molecules located in Photosystem II (Govindjee & Govindjee, 1975). Thus, the fluorescence quantum efficiency is variable, governed by the *in vivo* system responding to environmental attributes. It follows, therefore, that any environmental factors affecting photosynthetic processes (e.g. light, temperature, nutrient stresses) also have the potential to affect the fluorescence:chlorophyll *a* ratio.

Since chlorophyll fluorescence competes with photosynthesis for energy, it would therefore be expected that chlorophyll fluorescence would show an inverse relationship with the efficiency of photochemical processes. This phenomenon has been reported by several workers (Blasco, 1973; Harris, 1980; Karabashev & Solov'yev, 1976; Kiefer, 1973b) in both laboratory and natural phytoplankton populations.

Short-term variations in the photosynthesis of marine phytoplankton under conditions of alternating light and darkness have in fact been known for over 20 years (Doty & Oguri, 1957; Harris, 1973). Some authors have suggested that the amplitude and timing of these daily oscillations could be related to differences in species composition, cell size distribution, photoperiod, incident radiation and nutrient supply (Harding *et al.*, 1981;. Swift & Durban, 1972; Prezelin & Sweeney, 1977; Goering, Dugdale & Menzel, 1964; Eppley, Sapienza & Renger, 1978). Other field studies have further demonstrated the occurrence of significant diel fluctuations in photosynthetic capacity (McCaull & Platt, 1977; Prezelin & Ley, 1980) and suggest that the relationship between photosynthesis and light in natural phytoplankton communities is time-dependent, changing over the course of the day.

Research with dinoflagellates (Prezelin, Meeson & Sweeney, 1977; Prezelin & Sweeney, 1977; Govindjee, Wong & Govindjee, 1979; Harding, Meeson, Prezelin & Sweeney, 1981) has shown that both light-limited and light saturated photosynthesis are time dependent; these diel changes are unrelated to changes in cell pigment content or respiration; the periodicity of photosynthesis persists under constant conditions and is therefore not simply dependent on the light-dark cycle, but driven by a biological clock; inter-species specific differences may exist in the amplitude and timing of diel photosynthetic oscillations.

Further studies with natural phytoplankton assemblages dominated by pennate diatoms (Prezelin & Ley, 1980) suggest that similar relationships may occur in coastal waters. However, the extent to which diel periodicity of photosynthesis is a common characteristic of marine phytoplankton, with consistent and predictable features, rather than a phenomenon unique to the dinoflagellates, has been inadequately explored.

Karabashev and Solov'yev (1975), working at 2 stations in the equatorial Pacific, have reported a diurnal pattern in the fluorescence of phytoplankton chlorophyll operative over the entire photic zone in both homogeneous and stratified waters. These fluctuations were not co-phasal, so that the intensity of fluorescence in intermediate depths reached a peak 2-3 hours before the midnight maximum observed in the sub-surface and deep layers. The fluorescence ratio changed 7 or 8 times over the 24 hour period, reaching a low point at noon and a peak at midnight, indicating that the fluctuations are dependent on solar radiation. This finding was consistent with the data of other investigators (Blasco, 1973; Kiefer, 1973b) and with the fact that the diurnal pattern of solar radiation during the period of measurement remained the same, while the relative amplitude of diurnal fluctuations in chlorophyll fluorescence decreased with depth more quickly at 97°W than at 155°W - in keeping with the increase in water transparency along the equator from east to west.

Another factor which, by affecting photosynthetic processes, could affect the fluorescence:chlorophyll *a* ratio, is nutrient stress. Blasco (1973) showed that there was a relationship between nitrate deficiency and this ratio in limited volume cultures of *Skeletonema costatum*. The ratio increased immediately after the cells had exhausted the nitrate in the medium, ie the fluorescence increased when the culture stopped active growth, which was in perfect agreement with the hypothesis that the fluorescence of chlorophyll *a* competes with photosynthesis. For cultures with a less active growth, the photosynthetic activity will be low, and fluorescence per unit chlorophyll will be higher.

The relationship between nitrate deficiency and photosynthesis is, however, complicated. The assimilation of nitrate-nitrogen by autotrophic organisms requires an active complement of nitrogen-assimilating enzymes, energy in the form of ATP and reducing equivalents (NAD[P]H and ferrodoxin) and a source of carbon skeletons. In algae, the assimilation of nitrate and the synthesis of enzymes such as nitrate reductase are linked fundamentally with photosynthesis (Thacker & Syrett, 1972a, b; Thomas *et al.*, 1976).

From studies with freshwater algae such as *Ankistrodesmus braunii* and *Chlorella fusca* it has been shown that a period of nitrogen deficiency results in an enhanced capacity for nitrogen assimilation (Syrett, 1953; Hipkin, 1976), and a severe competition between

photosynthetic Carbon fixation and nitrogen assimilation for photogenerated electrons (Thomas *et al.*, 1976). Also exerting an influence in ammonium-grown cultures, is the appearance of nitrate reductase activity and the enhancement of other enzymic activities associated with nitrogen assimilation (Syrett & Hipkin, 1973; Hipkin & Syrett, 1977a,b).

Studies have also shown that nitrogen starvation enhances the uptake of inorganic and organic nitrogen in cultures of the marine diatom *Phaeodactylum tricornutum* (Rees & Syrett, 1979; Cresswell & Syrett, 1981; Shah & Syrett, 1982). This enhanced ability is energy dependent, requiring 10 electrons to reduce the nitrogen atom of nitrate to a nitrogen atom in an amino acid (Losada, 1980), and possibly additional energy to drive membrane transport. Further, it has been shown in *Chlamydomonas reinhardii* (Thacker & Syrett, 1972a) and *Dunaliella tertiolecta* (Grant, 1967, 1968; Grant & Turner, 1969) that nitrate assimilation is photosynthetically-dependent in nitrogen-replete cells. In nitrogen-replete cultures of *Chlorella fusca*, photogenerated energy may be used to drive nitrate assimilation and photosynthetic carbon fixation, whereas in nitrogen-deficient cultures, nitrate assimilation occurs at the expense of photosyntheitc carbon fixation (Thomas et al, 1976). Similar interactions between nitrate assimilation and photosynthesis have been observed in some marine diatoms (Falkowski & Stone, 1975; Terry, 1982).

In experiments performed by Hipkin, Thomas and Syrett (1983), the addition of nitrate to nitrogen deficient cultures of *Nannochloropsis oculata* and *Chlorella stigmatophora* resulted in an inhibition of photosynthetic carbon fixation. In these cultures nitrogen deficiency resulted in a decrease in cellular protein, chlorophyll and photosynthesis, although the efficiency of photosynthesis per unit chlorophyll increased. This suggests that photosynthetic carbon fixation in these cultures was limited by chlorophyll, with photogenerated electrons being used, preferentially, to drive nitrogen assimilation when nitrate became available. Since the addition of nitrate to such cultures does not inhibit light-dependent oxygen evolution, it is unlikely that nitrate inhibits photosynthetic electron transport.

In freshwater algae, nitrogen deprivation results in a number of physiological changes:- the accumulation of carbon reserves; decreases in the rate of photosynthesis; decreases in the rate of ribulose bis-phosphate carboxylase activity; increases in the capacity to assimilate nitrogen; increases in the activity of nitrogen-assimilating enzymes; a competition between carbon fixation and inorganic nitrogen assimilation for photogenerated electrons.

It has been shown (Rees, Hipkin & Syrett, 1979; Cresswell & Syrett, 1981; Shah & Syrett, 1982; Hipkin, Thomas & Syrett, 1983) that similar changes occur in nitrogen-deficient marine algae, enabling them to

assimilate nitrogen rapidly when it becomes available. This ability may allow these algae to scavenge for pulses of nitrogen which may become available intermittently as a result of the metabolic activity of heterotrophic organisms as proposed by McCarthy & Goldman (1979).

Therefore, if *in vivo* fluorescence is essentially excitation left over after the demands of photosynthesis have been satiated, and nitrogen deprivation results in a competition between photosynthesis and nitrogen assimilation for photogenerated electrons, as well as a decrease in cellular chlorophyll, it is possible that the physiological changes induced in the cell by nitrogen deprivation have the capacity to affect the fluorescence:chlorophyll *a* ratio. The fluorescence: chlorophyll *a* ratio of natural phytoplankton populations in nitrogen-deficient waters could therefore possibly be affected by nitrogen pulses resulting from the diel migration of zooplankton.

This problem of relating chlorophyll *a* concentration to fluorescence emission has attracted much attention. One line of research has been the study of the effects of the herbicide 3-(3,4 dichlorophenyl)-1, 1-dimethyl urea (DCMU). At concentrations as low as 3 μM (Bishop, 1958) it can completely inhibit photosynthesis by blocking electron transport at the level of Photosystem II (Duysens & Sweersk, 1963). Evidence suggests that the site of action could be cytochrome b-559 (Cramer, 1977; Roy & Legendre, 1979), and that H bonds may be involved in

binding DCMU to its site of action (Geissbuhler *et.al.*, 1979). The blocking causes the release of the accumulated excitation energy through alternative processes, especially fluorescence (Krey & Govindjee, 1966).

Slovacek & Hannan (1977) have shown that the *in vivo* fluorescence yield of *Phaeodactylum tricornutum* varies with culture conditions (eg. availability of nutrients), and that *Cyclotella nana* and *Chaetoceros galventonensis* show a species-dependent variation. Both types of yield fluctuations are reported to be eliminated when photosynthetic electron transport is blocked by adding DCMU, with *in vivo* fluorescence yields becoming maximal and a constant function of cellular chlorophyll *a*, regardless of growth conditions or of the species examined.

In the light of these findings, Slovacek & Hannan (1977) have suggested that DCMU-enhanced fluorescence emissions could be used to estimate the true level of chlorophyll *a* concentrations. However, DCMU-enhanced fluorescence (Fd):chlorophyll *a* ratios have been found to vary (Roy & Legendre, 1979), showing that the fluorescence yield is not always constant, even when the photosynthetic electron transport pathway is blocked. Thus Fd cannot always be used as an indicator of absolute chlorophyll *a* concentration in a phytoplankton population.

It has also been reported that DCMU generated no increase in fluorescence if added in the light (Papageorgiou, 1975). However, in experiments performed

by Roy & Legendre (1979), an increase in fluorescence was observed every time DCMU was added to samples which had not been dark-adapted.

Also important is the influence on the DCMU-treated fluorescence of the first light "shock" - laboratory tests have shown (*ibid.*, 1979) that parallel sampling, (whereby 2 subsamples are obtained, one treated with DCMU, and both then read on the fluorometer), as opposed to serial sampling (where a sample is read, DCMU added, and the sample read again) often had a slightly higher Fd. Another point is that most laboratory experiments have used green algae, and perhaps conclusions should not yet be extended to include all phytoplankton species.

Prezelin & Ley (1980), working on fluorescence rhythms in marine phytoplankton, indicate that where strong photosynthetic rhythms are present, the addition of DCMU to uncouple chlorophyll *a* fluorescence from photosynthesis may, in fact, enhance the fluorescence rhythm. If so, the Fd per µg chlorophyll *a* would become an even more unreliable indicator of chlorophyll *a* biomass than is fluorescence per µg chlorophyll *a* , in contrast to the suggestion by Slovacek & Hannan (1977) that there exists a constant *in vivo* fluorescence yield in the presence of DCMU.

As a result of work with natural phytoplankton communities, Cullen & Renger (1979) hypothesized that a low Fluorescence Response Index (FRI, i.e. the increase in fluorescence induced by DCMU) measured in the field

represents some sort of physiological stress on the population level. The manifestation of this stress would be an increase of the relative proportions of photosynthetically inactive fluorescence components, eg. the contributions made by dissolved fluorescence (Herbland, 1978), phaeophytin, or photosynthetically inactive algae. Such fluorescence, not directly associated with photosynthesis, and insensitive to DCMU, would affect the FRI.

It would appear, therefore, that many of the problems which beset the use of *in vivo* fluorescence measurements (eg, light, nutrient stress, etc.,), may also apply to DCMU-enhanced fluorescence.

1.7. Objectives of present study

In the light of the accumulating evidence to suggest that frontal zones may be biologically quite distinct from the water masses on either side, a series of oceanographic surveys was undertaken in order to establish whether the monitoring of biological characteristics offered a real-time system for the detection of fronts and their associated water masses.

An initial investigation into detecting frontal systems using biological indicators was conducted in collaboration with AUWE and IMER (Institute of Marine Environmental Research) in the Alboran Basin in November 1981 where one of the most pronounced fronts in the Mediterranean occurs (Woods and Watson, 1970; Cheney, 1977). It is created by

the swift Atlantic water jet which flows through the Strait of Gibraltar and meanders about 500km eastward through the Alboran Basin to the prime meridian (Stevenson, 1977) and is restricted to the upper 200m (Levine & White, 1972). The most distinguishing characteristic of the frontal system is the anticyclonic gyre found in the western basin between Spain and Morocco between 4°W and 5°W, although Ovchinnikov *et al* (1976) have argued that this gyre is an anomaly created by unusual northwest winds during particular summers. However, various other workers contend that the large, anticyclonic gyre is a persistent feature of the western Alboran Sea, at least during late spring and summer, regardless of the prevailing wind direction (Donguy, 1962; Cheney, 1977, 1978; Grousson & Faroux, 1963; Lacombe *et al*, 1964; Stevenson, 1977). Data for other seasons is limited, but those that do exist (Cheney, 1978; Lucaya & DeCastillejo, 1972) indicate that the gyre is a normal feature of the circulation pattern and persists throughout the year, along with a series of alternating cyclonic and anticyclonic gyres to the east of the main anticyclonic gyre.

The aim of the survey carried out in November 1981 was to investigate both the horizontal and vertical distribution of temperature, salinity and chlorophyll across the front in the Alboran Basin. Chlorophyll *a* was chosen as the biological parameter to be investigated as it was possible to obtain continuous surface measurements

of chlorophyll *a* fluorescence (Chl F) using a flow-through system connected to the ships fire-main system.

The front was located, and it was found that both the in-flowing Atlantic Water at the northern boundary of the gyre, and the Gyre Water could be characterized by their sea surface temperature (SST), salinity and chlorophyll *a* fluorescence values. A high correlation was found between temperature and salinity in crossing the front between the Atlantic Water and the Gyre Water, but the chlorophyll data showed no correlation with either temperature or salinity in crossing the front, despite the fact that both the Atlantic Water and the Gyre Water could be characterized by typical chlorophyll *a* fluorescence values. These results indicated that the lack of correlation between chlorophyll *a* fluorescence and temperature and salinity was due to the fact that the chlorophyll response on changing water masses preceded both temperature and salinity responses. This suggested that not only could the front be detected by continuous monitoring of a biological parameter, but that the real-time monitoring of *in vivo* chlorophyll fluorescence levels might offer a potential "early-warning" alarm when approaching a frontal system.

A further survey was carried out on the Ushant front during June 1982 in order to investigate whether similar results were obtainable for a shelf sea front, and to determine the distance advantage, if any, gained by using

chlorophyll *a* fluorescence as a detector of a shelf sea front.

This was followed by a survey of the same front in June 1984 to determine both alarm and false alarm rates using chlorophyll *a* fluorescence measurements as a real-time detection method and to compare these rates with those obtained using temperature as a detection method. Studies were also undertaken to investigate the effect of DCMU addition on the fluorescence of natural populations of marine phytoplankton across a shelf-sea front, and the effects of diurnal variation on *in situ* chlorophyll *a* fluorescence. The distribution of adenosine tri-phosphate (ATP) and pH were also investigated.

SECTION 2

2. METHODS

2.1. Conduct of Trials.

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2. METHODS

2.1 Conduct of Trials.

Survey areas were selected on the basis of the historical record, and the trials carried out on board Royal Marine Auxiliary Service (RMAS) vessels. The surveys were therefore strictly confined to these predetermined areas, as work in submarine exercise areas required prior clearance from Fleet, and was also limited by territorial waters.

Navigation was by SATNAV in the Alboran Basin, and by SATNAV and DECCA on all other surveys.

Vertical profiling stations were chosen on the basis of prior surface monitoring during the trial, with the sampling regimes for nutrient and pigment analysis being dictated by the temperature and/or chlorophyll profiles at a particular station.

2.2 Temperature and Conductivity.

Monitoring of sea surface temperature (SST) and salinity in the Alboran Basin was carried out using a Partech TSD-81 instrument, consisting of a remote temperature compensated electrolytic conductivity probe with a built-in high speed temperature sensor. This was connected to a deck unit for direct readout of temperature and computed salinity readings.

The Partech unit was placed in a flow-through system, in parallel with a Turner fluorometer, using water

obtained from the ship's fire main system. The flow rate past the Partech was approximately 30 l min^{-1} (about 8 times greater than that used for the Turner fluorometer).

This instrument was battery-powered, and since no indication as to the state of charge was available, erroneous results were sometimes obtained as a result of the batteries discharging.

Continuous monitoring of sea surface temperature and conductivity was therefore carried out in all other areas using an NBA (Controls) Ltd CTU-1 sensor based on the NBA Model IDC-2 inductive conductivity probe. The thermistor and inductive conductivity sensor, which are mounted within the sample chamber, continuously sample the surrounding water and the acquired readings are displayed digitally. An inductive conductivity cell ordinarily requires a minimum volume of water (approx. 50 gallons) for accurate measurement. Since the sensor of the CTU-1 monitors a constant volume of water, any deviation caused by the lower water volume is corrected for by calibration of the sensor whilst in the measuring chamber. The output from the probe is therefore scaled before being digitally displayed.

Details of the thermal structure of the water column were obtained using expendable bathythermographs (XBTs), with the data being stored on a Sippican Mk 8 XBT recorder.

Conductivity/Temperature/Depth (CTD) data for vertical profiles were obtained using a Neil Brown instrument

deployed by the Admiralty Research Establishment (ARE - formerly AUWE).

2.3. Chlorophyll Measurement

In vivo chlorophyll *a* fluorescence emissions (Lorenzen, 1966) were continuously monitored using a Turner Design Model 10 Fluorometer for surface mapping and an Oriel Sub-AquaTracka for vertical profiling. Discrete water samples were subjected to pigment analysis using spectrophotometric techniques.

2.3.1. Turner Model 10 Fluorometer:

This instrument is a ratio fluorometer, incorporating a flow-through cell, in which the strength of the *in vivo* chlorophyll *a* fluorescent emission is compared to that of the exciting light. For the trial in the Alboran Basin, the instrument was calibrated to give a full-scale deflection of 31,000 Turner Units (tus) at a concentration of 10 mg m^{-3} of chlorophyll *a*, using an acetone extract of the alga *Chlorella vulgaris*. On all subsequent trials, a suspension of the alga *Phaeodactylum tricornutum*, the chlorophyll *a* content of which had been determined spectrophotometrically was used.

The excitation source was a blue fluorescent lamp (F4T5), the light from which was passed through a Corning CS 5-60 filter. The main excitation energy was therefore at about 445nm. The fluorescence emission passed through

a Corning CS 5-64 filter, excluding wavelengths below 645nm, with maximum transmission at 650nm.

The standard S4 photomultiplier (RCA 931A) was replaced by a red-sensitive photomultiplier (R136) in order to extend the range of the instrument from 650nm to 750nm. Since *in vivo* chlorophyll has a maximum fluorescence at 685nm (Goedher, 1964), this modification increased the sensitivity to chlorophylls by a factor of approximately 10. A flow-through system was used in which the sample was irradiated for approximately 0.3 seconds.

These modifications were made so that the instrument measured mainly fluorescence from chlorophyll *a*, with some interference from chlorophyll *b*, but practically none from chlorophyll *c*.

The amount of fluorescence measured by the photomultiplier registered on a dial which read from 0-100, and the 0-10 mV output was continuously recorded on a Servogor multichannel recorder.

The sensitivity of the fluorometer was altered by varying the amount of light exciting the sample by means of four different sized apertures in a range selector (x1, x3, x10 & x30), each of which had a discrete voltage signal of between 0 to 1 Volt which could also be recorded. Selection could be carried out either manually or automatically. On automatic mode, a more sensitive range was selected when the reading fell below 20% of full-scale deflection. Conversely, a less sensitive range was selected when the reading went off-scale.

In order to express the fluorometer readings as quantities of chlorophyll *a* per litre of seawater it is necessary to calibrate the instrument against known values of chlorophyll *a*.

The fluorometer was calibrated using pure cultures of the alga *Phaeodactylum tricornutum* whose chlorophyll *a* concentration had been determined by u.v. techniques. Absorbance of the extracts were measured at 630nm, 645nm & 750nm, and the extinction coefficients, ϵ, calculated. Chlorophyll *a* concentrations were then calculated using the following equation (SCOR-UNESCO, 1966):

$$\text{Chl } a = 11.64\ \epsilon_{663} - 2.16\ \epsilon_{645} + 0.1\ \epsilon_{630}\ \mu g\ l^{-1}$$

Where

$$\epsilon_{663} = Abs_{663} - Abs_{750}$$

$$\epsilon_{645} = Abs_{645} - Abs_{750}$$

$$\epsilon_{630} = Abs_{630} - Abs_{750}$$

(Subtracting the absorbance values at 750nm corrected for turbidity of the sample)

To calibrate the Turner, the culture was diluted to give an *in vivo* suspension equivalent to 10 $\mu g\ l^{-1}$.

The range of *in vivo* chlorophyll concentrations measured by this instrument is 0.04 to 15.0 ppb ($\mu g\ l^{-1}$).

2.3.2 Oriel Sub-AquaTracka:

This instrument was used to obtain vertical chlorophyll profiles. The excitation source, a pulsed xenon light, gives a continuous output, and the instrument incorporates a double beam system, each beam having an independent photodiode detector. A reference channel monitors the light source intensity directly, and adjusts for reduced output due to ageing of the lamp.

2.4. Pigment Analysis.

The fluorescence emission monitored by the Turner and Oriel fluorometers is not necessarily due solely to chlorophyll *a* - a contribution could also be made by other chlorophylls and breakdown products such as phaeophytin. The extent to which this occurs will be dependent on numerous factors, including species variation and the physiological condition of the organisms.

In order to measure the concentrations of chlorophyll pigments and breakdown products, discrete water samples were collected, filtered and extracted into an organic solvent. The extracts were then subjected to spectrophotometric analysis, and chlorophylls *a*, *b*, *c* and phaeophytin *a* levels calculated using equations derived by Jeffrey and Humphrey (1975).

The procedure for extracting chlorophyll during the surface monitoring programme was to take a 1 litre sample of seawater direct from the Turner fluorometer outflow. Nansen bottles were used to collect 1 litre samples during

vertical profiling to calibrate the Oriel. To prevent further pigment breakdown 1ml of 1% magnesium carbonate suspension was added to the sample. The sample was then filtered through a Whatman glass microfibre filter using vacuum filtration. The filter paper was then removed, folded residue-side inwards, and pressed dry between filter papers. Where on-board analysis was not possible, filters were stored (for subsequent laboratory analysis) at -20°C to prevent pigment breakdown (Nightingale, 1982).

The dried filter paper was placed in a McCartney bottle, which had been covered in aluminium foil to prevent light degrading the sample, manually macerated for 3 minutes in 9.9 mls of 90% aqueous acetone and 0.1 ml of methanol and allowed to stand in a dark place for 20 minutes. The supernatant was then decanted off, and syringed through a Whatman glass microfibre filter to remove any remnants of original filter. Using a Pye Unican SP1800 spectrophotometer with 4cm path length cells, readings were taken at 630nm, 645nm, 663nm and 750nm, and the chlorophyll concentrations calculated using the following equations (Jeffrey & Humphrey, 1975):

$$\text{Chl } \underline{a} = [11.64(\epsilon_{663}) - 2.161(\epsilon_{645}) + 0.1(\epsilon_{630})]v/V \text{ mg } m^{-3}$$

$$\text{Chl } \underline{b} = [-3.94(\epsilon_{663}) + 20.97(\epsilon_{645}) - 3.66(\epsilon_{630})]v/V \text{ mg } m^{-3}$$

$$\text{Chl } \underline{c} = [-5.53(\epsilon_{663}) + 14.81(\epsilon_{645}) + 54.22(\epsilon_{630})]v/V \text{ mg } m^{-3}$$

Where

$\epsilon_{663} = Abs_{663} - Abs_{750}$

$\epsilon_{645} = Abs_{645} - Abs_{750}$

$\epsilon_{630} = Abs_{630} - Abs_{750}$

v = volume of extract (ml)

V = volume of seawater (l)

(Subtracting the absorbance values at 750nm corrected for turbidity of the sample.)

In order to calculate the phaeophytin concentration, readings of the extract were taken at 665nm and 750nm before and after acidification with 0.5ml of N HCl: initial readings were recorded, 0.5 ml of N HCl were added to the extract, and absorptions again measured at 665nm and 750nm after storing for 30 minutes in the dark.

Concentrations of chlorophyll *a* and phaeophytin *a* were then calculated using the following equations (Lorenzen, 1967):

$$\text{Chl } a = 26.73(665_o - 665_a)v/VL \quad mg\ m^{-3}$$

$$\text{Phaeo } a = 26.73[1.7(665_a) - 665_o]v/VL \quad mg\ m^{-3}$$

Where:

665_o = (Absorbance 665nm - Absorbance 750nm) before acidification

665_a = (Absorbance 665nm - Absorbance 750nm) after acidification

v = volume of extract (ml)

V = volume of sample (l)

L = path length of cell (cm)

2.5 Adenosine Triphosphate (ATP).

The chemical breakdown of carbohydrates, fats and proteins by the respiratory metabolism of both plant and animal cells releases energy. This is used, as is the energy derived from photosynthesis, in the synthesis of a phosphate compound, adenosine triphosphate (ATP). ATP can then act as an energy donor for the wide variety of biochemical reactions inside cells. ATP is thus a means by which the energy derived from sunlight or from food metabolism may be stored within the cells and released when required. Cellular ATP can be determined by enzymatic estimation, utilizing luciferase.

Light emission in the firefly *Protinus pyralis* has been shown to be dependent on ATP (McElroy, 1947; McElroy & Strehler, 1949; Strehler & Trotter, 1952), with crude extracts of luciferase from the firefly abdomen showing an *in vitro* luminescence which is dependent on ATP concentration. The production of light from this reaction forms the basis of the enzymatic estimation of ATP. The reaction occurs in two stages (Karl & Holm-Hansen, 1976):

1) $LH_2 + ATP + LUCIFERASE + Mg^{2+} \longrightarrow E\text{-}LH_2\text{-}AMP + PP_i$

2) $E\text{-}LH_2\text{-}AMP + O_2 \longrightarrow$ OXYLUCIFERIN + LUCIFERASE + CO_2 + AMP + hv

Where

LH_2 = luciferin

AMP = adenosine monophosphate

PPi = pyrophosphate

$E\text{-}LH_2\text{-}AMP$ = Dehydroxyluciferin-AMP complex.

hv = light

The substrates required for this reaction are luciferin, oxygen and ATP, with bivalent metal ions (especially Mg^{2+}) being required as co-factors in the reaction. When luciferin and luciferase are in excess, the concentration of ATP will limit the rate of the reaction, with light production being proportional to the concentration of ATP.

Although a relatively simple assay technique, the reliability of the method is dependent upon certain constraints:

1) Cellular ATP must be extracted without the degradation of the molecule by hydrolytic enzymes present within the cell. Therefore, cellular ATPases must be denatured prior to ATP extraction.

2) Since the assay technique is enzymatic, it is sensitive to environmental changes, i.e. temperature, pH and inhibition from anions and cations (Patterson *et al*, 1970). Even if these factors are constant, light production may be quenched due to absorption by compounds or structures (eg. cells) present in the sample.

Cellular ATP estimations were performed using the light production from the enzymatic reaction of ATP with luciferin and luciferase, and assayed using the Lumacounter M2080 (Lumac, B.V., Post Bus 31101, 6370 AC Schaesberg, The Netherlands). This instrument allows the estimation of ATP by either peak height analysis or interpretation of the light decay curve for 10, 30 or 60 seconds. Enzyme injection can be either automatic or manual, with the enzyme being added to the reaction cuvette in the counting chamber. ATP levels are represented on a digital display unit, corresponding to Relative Light Units (RLUs). The photomultiplier gives maximum sensitivity between 375nm and 620nm.

Estimates of cellular ATP were carried out by incubating duplicate samples (100µl) with 100µl of Nucleotide Releasing Agent (Bacteria) (NRB) for time periods previously found to result in maximal extraction of ATP from cells contained in a cuvette (10 secs). At the end of the incubation period, 100µl of reconstituted "Lumit" enzyme (Lumac, *ibid*) was added to the cuvette and the cuvette immediately placed in the counting chamber. The integration of the light decay curve was initiated 5 secs after enzyme addition, and the RLUs recorded for each sample.

For standardisation of enzyme preparation over 24 hours, an ATP standard (0.02 µg ml^{-1}) was measured at the beginning and end of the experiments. The ratio of RLUs

from the ATP standard at zero time, and after 24 hours was calculated, and used to correct the sample counts.

2.6. Particle Size Counts

The Coulter Counter was originally developed as an instrument to count red blood cells (Coulter, 1953), and has subsequently been applied to many areas of study where estimates of numbers of small sized particles and their volumes are required.

Some of the earliest work using the Coulter counter with unicellular marine algae was reported by Hastings *et al.*, (1962); Maloney *et al.*, (1962) and El-Sayed *et al.*, (1963). In the latter study, growth curves for many species were produced. Similar studies were performed on *Phaeodactylus tricornutum* by Bently-Mowat & Reid (1977), whilst Gray (1973) was able to follow the growth characteristics of a protozoan species.

However, problems can be encountered when multi-cellular species are used because of increased error in estimates of population numbers (Evans & McGill, 1968; Ilmarivata, 1974). For instance, when budding of a cell occurs, parent and daughter cells may register as a single, large cell (Zellner *et al.*, 1963).

However, under certain circumstances, the shape of the cell can aid in its analysis: Hastings *et al.* (1962) found that long, rod-like cells of *Rhizosolenia* were orientated with the long axis in the direction of

electrolyte flow into the orifice tube. The cells were counted using a 140μm diameter orifice tube, even though the cells were in the order of 290μm in length.

In the present study, it was hoped to compare particle size counts with ATP estimations and chlorophyll fluorescence measurements as estimates of phytoplankton biomass (Hughes, 1985).

The counter consists of three basic parts: a glass orifice tube with an electrode on either side; a mercury manometer system (of which the orifice tube is an integral part); and a cathode ray oscilloscope (CRO) and decade counter.

A constant current is established between the electrodes via the electrolyte, passing through the small orifice at the base of the glass tube. Particles suspended in the electrolytes are sucked inside the glass tube by the mercury manometer system, and as they pass through the orifice, the particles produce a specific change in resistivity between the electrodes, proportional to the size of the particles. The discrete changes in resistance are transmitted as electrical impulses to the decade counter and CRO monitor, with each pulse being registered as a single digit on the decade counter. Thus, by sampling specific volumes of known dilution, the concentration of particles in suspension can be calculated from the digital count of the sample. In addition, by

using suspensions containing particles of known mean volume, estimates can be made of particle volumes from test suspensions. This process is further simplified by the addition of a Channelyzer C-1000 with which both estimates of particle volume and size and/or volume distributions can be made.

The pulses produced by the particles are arranged in order of increasing size. The frequency of these pulses can then be analysed, and a size distribution curve obtained which is displayed visually on the CRO across 100 channels. Using the integration mode on the Channelyzer, a numerical description of the distribution curve is obtained which can be converted to hard-copy using an X-Y plotter, or presented as digital information via a teleprinter.

2.7 Nutrient Analysis

Continuous sea surface mapping was carried out by continuous injection techniques using a Chemlab Automatic Analyser, the seawater having first been passed through a filtration unit containing a 0.45 μm filter. The analyses were carried out using colorimetric techniques, with absorptions measured using a multichannel flow-through colorimeter fitted with 50mm path length cells. The automated procedure for the determination of orthophosphate depends on the reaction of ammonium molybdate in acid medium to form molybdo-phosphoric acid,

which is then reduced *in situ* to molybdenum blue by ascorbic acid. The colour is then measured using 880nm interference filters.

Silicate ions were similarly reacted to form silicomolybdate complexes, and absorption measured at 880nm. Interference from phosphate was eliminated by the addition of tartrate ions.

Determination of nitrate is based on the formation of a diazo compound between nitrite and sulphanilamide, which is then coupled with napthylethylenediamine hydrochloride to form a reddish-purple azodye. The colour is then measured at 540nm.

Nitrate concentrations were estimated after reduction of nitrate to nitrite by passing the sample through a cadmium/copper reduction coil, followed by the standard nitrite technique. Nitrate was then estimated by subtracting initial nitrite levels from the total nitrite (after reduction of nitrate to nitrite).

Calibration and baseline checks were carried out at regular intervals throughout the trial.

2.8. pH.

pH levels were continuously monitored by an EIL Model 7055 pH meter, the electrodes of which were fitted into a flow-through cell. The pH meter was set on the 0 - 14 scale, giving an accuracy of +/- 0.02 pH units.

2.9. Statistical Analysis

The relationship between the data sets measured during the trials was determined using a Hewlett-Packard 9816S computer by calculating the product moment correlation coefficient, r, from the formula

$$r = \Sigma' xy \; / \; (\Sigma' x^2)(\Sigma' y^2)$$

Where

x and y are the two data sets to be compared

n is the number of pairs of data sets

$\Sigma' xy = \Sigma xy - (\Sigma x)(\Sigma y) / n$

$\Sigma' x^2 = \Sigma x^2 - (\Sigma x)^2 / n$

$\Sigma' y^2 = \Sigma y^2 - (\Sigma y)^2 / n.$

2.10. Data Storage (Sea Surface Monitoring)

2.10.1. Alboran Basin

During the survey carried out in the Alboran Basin in November 1981 (Section 3), sea surface monitoring data were recorded manually at 5 minute intervals.

2.10.2. Seasonal surveys

During the seasonal surveys carried out around the British Isles for the period September 1982 to August 1983 (Section 4), continuous analogue signals from sensors were recorded on a Servogor multichannel chart recorder, and on magnetic tape using a Racal Store 7 DS recorder.

2.10.3. Rates of change in physio-chemical parameters

During the investigation into the rates of change in physiochemical parameters across the Ushant front in June 1984 (Section 5), continuous analogue signals were recorded on a Servogor multichannel recorder, and on a data aquisition system supplied by Computing and Communication Services (CCS), Bodmin.

On the CCS system, analogue signals from each sensor were converted to digital form using an Apoloco Flexy S4 microprocessor, and readings at 10 second intervals stored on magnetic tape using a Tracker 1600 data storage system. Data from each sensor were then averaged over one minute, and this value displayed on a DEC LA34 graphics plotter, and in digital form on a DEC LA34 printer.

SECTION 3.

3. INITIAL INVESTIGATION INTO DETECTING FRONTAL SYSTEMS USING BIOLOGICAL INDICATORS.

3. INITIAL INVESTIGATION INTO DETECTING FRONTAL SYSTEMS USING BIOLOGICAL INDICATORS

3.1. INTRODUCTION

An initial investigation into detecting frontal systems using biological indicators was conducted in the Alboran Basin in November 1981, where one of the most pronounced fronts in the Mediterranean occurs (Cheney, 1977). The trial was conducted in collaboration with AUWE and IMER .

Although a number of biological parameters were considered for investigation (see: Section 1.), the distribution of chlorophyll *a* was thought to show the greatest potential as a detection method since existing methodology, i.e. the measurement of chlorophyll *a* fluorescence (Chl F), made it possible to obtain real-time continuous measurements.

3.2. STUDY AREA.

3.2.1. Survey 1.

An initial survey was carried out in the Alboran Basin on the 9-10 November, 1981, in order to locate the position of the front between the in-flowing North Atlantic Water (NAW) and Gyre Water (GW) i.e. NAW modified

by its long residence time in the Mediterranean. Sea surface temperature (SST), salinity and chlorophyll *a* fluorescence (Chl F) levels were monitored, and a series of expendable bathythermographs (XBTs) taken. Figure 5 shows the ship's track and the positions of the XBTs.

3.2.2. Survey 2.

On the 10 November, an attempt was made to obtain a series of vertical temperature and chlorophyll *a* profiles across the well-defined front identified in the northwest of the survey area (a). The ship's track and the positions of the vertical profile stations (Figure 6) were chosen on the basis of the initial survey (9-10 November).

3.2.3. Survey 3.

As the front was not found on 10 November, and all the profiles were taken in NAW, a further, more extensive survey was carried out on the 11-12 November (Figure 7a).

3.2.4. Survey 4.

On 12 November, the front between NAW and GW was re-located using sea surface monitoring of SST, salinity, chlorophyll *a* fluorescence (Chl F) and XBT profiles, and a series of vertical temperature and chlorophyll *a* profiles made across it (Figure 7b).

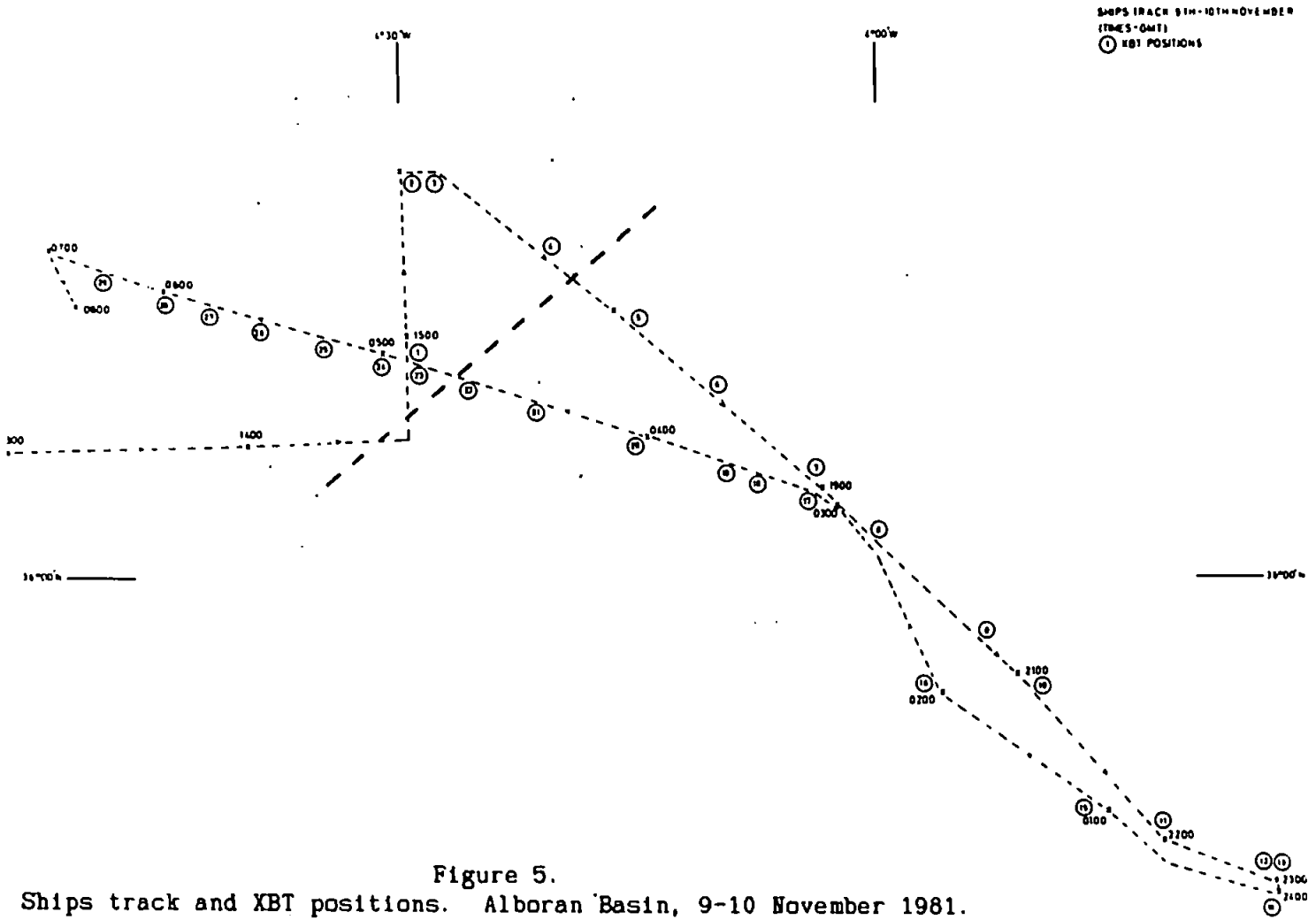


Figure 5.
Ships track and XBT positions. Alboran Basin, 9-10 November 1981.
--- Front between NAW and GW.

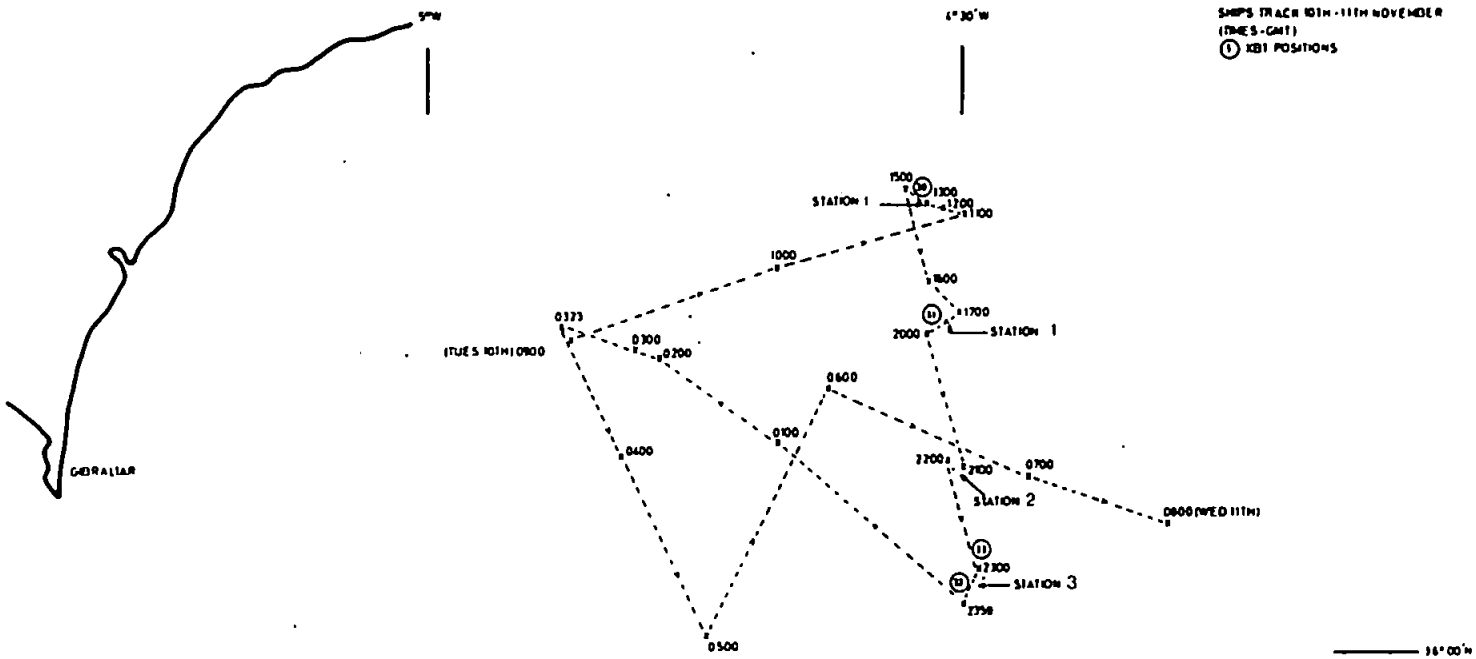


Figure 6.
Ships track and profile stations. Alboran Basin, 10-11 November 1981.

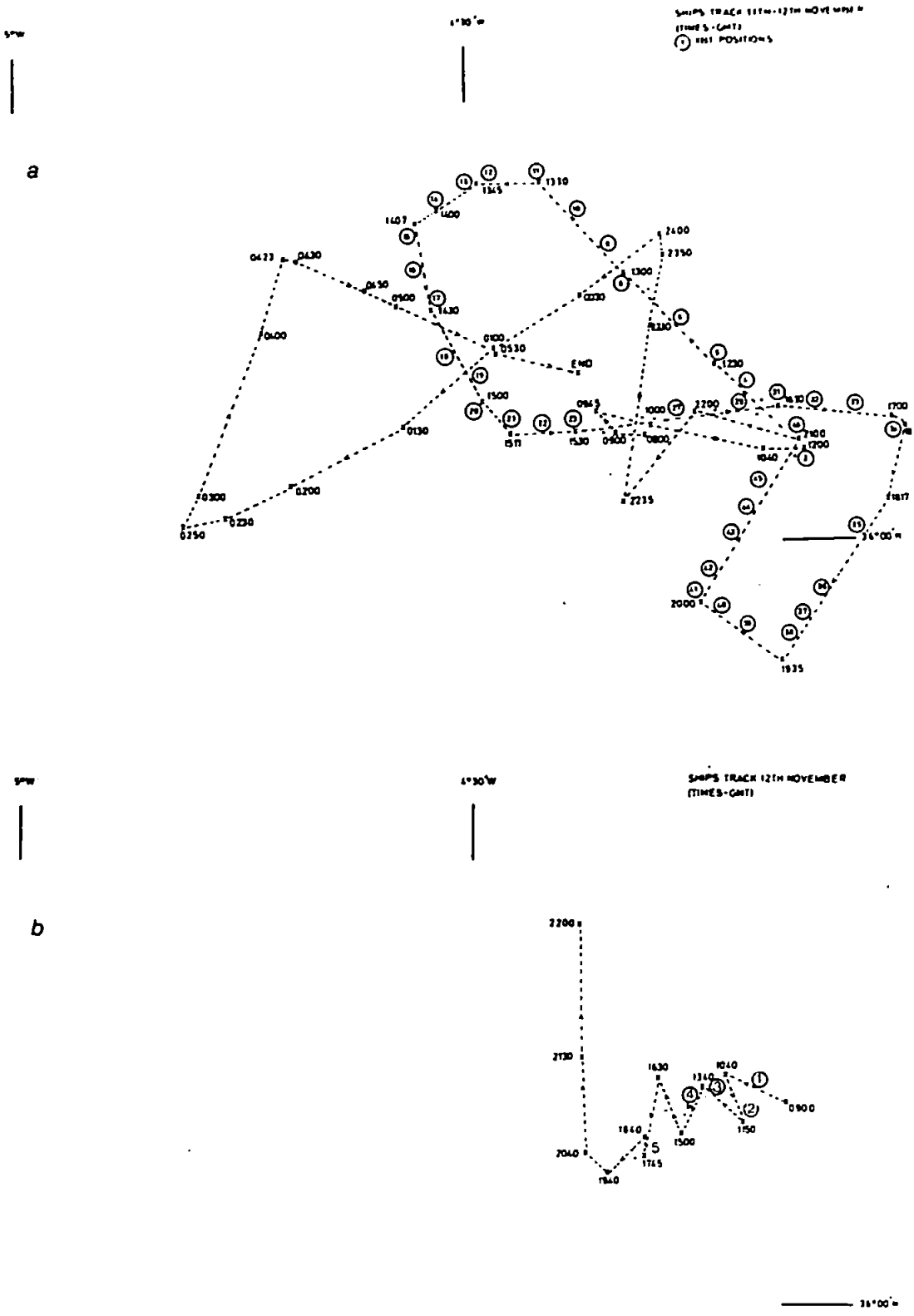


Figure 7.
Alboran Basin. (a) Ships track and XBT positions, 11-12 November 1981. XBTs 2 to 10 were taken along the front between NAW and GW. (b) Profile stations, 12 November 1981.

3.3. RESULTS.

3.3.1. Survey 1: 9-10 November (Figure 5)

Surface Measurements

On transit 1 (stations 2 to 13) SST was < 19.0°C at stations 2 and 3, increasing to 19.5°C at station 4 and and 20.0°C at station 5. SST continued to increase (less rapidly) to 20.4°C at station 10, then fell gradually to 19.1°C again at station 13.

On transit 2 (stations 14-29) SST was steady at 19.1°C from station 14 to station 15, then increased rapidly to 20.1°C at station 16, thence gradually to 20.6°C at stations 19-21, thereafter falling again gradually to 19.0°C.

Chl F varied from 44 to 60 Turner units (tus) at stations 2 to 4, falling to 30 tus at station 5, and remaining constant at 26-30 tus from station 5 to station 23. Chl F values then increased steadily to 43 tus at station 25, varying from 47-62 tus between stations 25 to 29.

Salinity varied from 36.4-36.6‰ at stations 1, 2, and 3, increasing to 36.8‰ at station 4 and remaining between 36.9 and 37.1‰ at stations 5-15. At stations 16-21 salinity increased to 37.2-37.3‰ then decreased to 36.7‰ at station 22. Results for stations 23-29 are not reliable, due to instrument failure.

Depth Profiles

XBT data for 9-10 November (Appendix 1) indicate that the first transit (southeast) started in non-stratified NAW, characterized by a SST of 18.9°C, salinity of 36.4‰ and Chl F values of around 57 tus.

By station 4, the ship had passed into GW, characterized by a SST of approximately 20.2°C, a salinity of 37.1‰ and Chl F of around 28 tus. Station 4 showed two major differences from stations 2 & 3: SST increased by 1.5°C, with a mixed layer from the surface to about 15m and a thermocline between 15 - 150m, with a temperature inversion (typical of a front) at about 75m.

At stations 11-15 inclusive, XBT data indicate that the ship was now in an area of cooler water overlying GW with a SST of 19.1°C, salinity 36.8‰ and Chl F of about 30 tus. Stations 10 & 15 again exhibit the temperature inversion typical of frontal regions. SST in this south eastern area indicate that the ship was again in NAW; salinities indicate an intermediate water mass, and chlorophyll values indicate that the ship was still in GW. This was attributed to crossing a front from GW into south-flowing NAW that is forming the boundary at the eastern edge of an anticyclonic gyre, an assumption later confirmed by satellite data.

On the second transit (northwest) the ship remained in GW from stations 16-23, and at station 24 had again passed into non-stratified NAW.

3.3.2. Survey 2: 10-11 November (Figures 6 & 8)

Figure 8 shows the temperature and Chl F' profiles for stations 1-3. Chlorophyll fluorescence was measured using an Oriel fluorometer, and the fluorescence readings recorded on the log scale of the instrument were converted into mg m^{-3} of chlorophyll *a* (Chl F').

Profile station 1

Temperature ranged from 18.8-13.3°C. SST was 18.8°C, falling to 18°C at 14m. There was a strong thermocline between 18 and 23 metres, with corresponding temperatures of 17.5 and 14.5°C. The water column remained virtually isothermal at 14.4°C to 60m, with a slight temperature inversion (rising to 14.7°C) at 60-70m, then fell gradually to minimum (13.3°C) at, and below, 120m.

Chl F' ranged from 0.2 - 2.9 mg m^{-3} with maximum values at, and above, the thermocline, falling from maximum (2.9 mg m^{-3}) at 0-15m to 0.3 mg m^{-3} at 22m, then rising slightly to 0.6 mg m^{-3} at 30-38m, then falling to minimum (0.2 mg m^{-3}) at 40m and below.

In vitro measurements showed that phaeophytin *a* was not detectable throughout the water column (0-150m). Nitrate (NO_3) ranged from 0.11 to 1.29 ppb, falling slightly from 0.19 ppb at 0m to minimum (0.11 ppb) at 50m, then rising to 1.20 ppb at 50m (over the area of the temperature inversion) and to maximum (1.29 ppb) at 150m. Silicate (SiO_3) ranged from 2.4 to 10.2 ppb, increasing steadily from minimum (2.4) at 0m to maximum (10.2 ppb) at 100m,

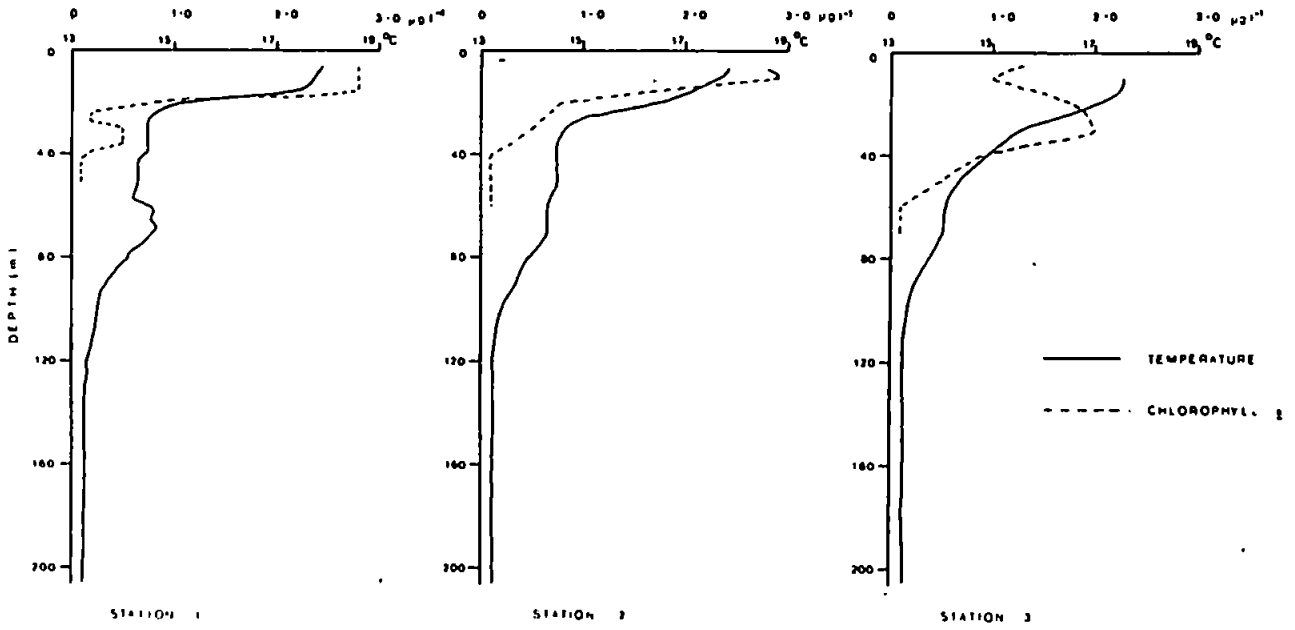


Figure 8.
Profile Stations 1 - 3, 10 November 1981. Distribution of temperature (°C) and chlorophyll *a* (mg m^{-3}) with depth.

then falling slightly to 10.0 ppb at 150m. Phosphate (PO_4) ranged from 0.42 to 0.67 ppb, rising steadily from minimum (0.42) at 0m to 0.66 ppb at 100m, and 0.67 ppb at 150m.

Profile station 2

Temperature ranged from 18.5-13.3°C, falling steadily from 18.5°C (maximum) at 3m to 14.5°C at 30m, then very gradually to 14.3°C at 70m, then more sharply to minimum (13.3°C) at, and below, 120m.

Chl F' ranged from 0.2-3.0 mg m^{-3}, falling sharply from maximum (3.0 mg m^{-3}) at 10m to 0.75 mg m^{-3} at 20m (with no correspondingly sharp step in the temperature profile), then more gradually to minimum (0.2 mg m^{-3}) at, and below, 40m.

In vitro measurement of phaeophytin *a* showed that it was not detectable at 0, 20, or 100m, but was present at a level of 2.04 mg m^{-3} at 50m, corresponding with increases in NO_3, PO_4 and SiO_3. NO_3 ranged from 0.86 to 3.89 ppb, falling slightly from 0.98 ppb at 0m to 0.86 ppb at 20m, then rising below the base of the thermocline to 3.44 ppb at 50m, and reaching maximum (3.89 ppb) at 100m. SiO_3 ranged from 1.9 to 11.4 ppb, rising from minimum (1.9) at 0m to 3.2 ppb at the thermocline (20m), then more sharply to 11.4 ppb (maximum) at 50m before dropping slightly to 10.6 ppb at 100m. PO_4 ranged from 0.34 to 0.66 ppb, falling from 0.41 ppb at 0m to minimum (0.34 ppb) at the base of the thermocline at 20m, then rising more sharply

to 0.66 ppb (maximum) at 50m and remaining relatively constant to 100m (0.65 ppb).

Profile station 3

Temperature ranged from 18.6-13.3°C, falling steadily from maximum (18.6) at 3m to minimum (13.3°C) at, and below, 60m. There was no definite thermocline, with the top 80m of the water column being fairly well mixed.

Chl F' ranged from 0.2-2.0 mg m^{-3}, falling from 1.25 mg m^{-3} at 4m to 1.0 mg m^{-3} at 10m, rising to maximum (2.0 mg m^{-3}) at 30m (not corresponding to any step in the temperature profile), then falling to minimum (0.2 mg m^{-3}) at, and below, 60m, the bulk of the chlorophyll being at 10-40m.

In vitro phaeophytin *a* was not detectable throughout the water column from 0 to 110m. NO_3 ranged from 1.92 to 3.99 ppb, with the highest values being in the top 50m of the water column. NO_3 dropped slightly from maximum (3.99 ppb) at 0m to 3.81 at 20m and 3.06 ppb at 50m, then to minimum (1.92 ppb) at 110m. SiO_3 ranged from 6.4 to 12.2 ppb, rising from minimum (6.4ppb) at 0m to 7.0 ppb at 20m, then rather more sharply to 10.7 ppb at 50m, and more gradually to maximum (12.2 ppb) at 110m. PO_4 ranged from 0.44 to 0.75 ppb, rising steadily from minimum (0.44 ppb) at 0m to maximum (0.75 ppb) at 110m.

3.3.3. Survey 3: 11-12 November (Figure 7a)

Surface Measurements

On transit 1 (XBT stations 1 to 33) SST rose from 20.7°C at station 1 to 20.9°C at stations 4-9, then fell steadily to 19.1°C at station 18, and remained fairly constant at 19.1-19.2°C from station 18 to station 29, rising to 20.5°C at station 33.

Chl F ranged from 27-65 tus, being fairly constant at around 28 tus from station 1 to station 7, then rising gradually to 65 tus at station 18, and varying slightly from 55 to 65 tus from station 18 to station 29. Chl F then fell sharply to 28 tus at stations 32 and 33.

Salinities ranged from 36.9 to 37.5‰, rising slightly from 37.4‰ at station 1 to 37.5‰ at stations 2 to 11, dropping slightly to 37.4 at stations 12 and 13, then more sharply to 37.0‰ at station 16, and remaining at 36.9 to 37.0‰ at stations 16 to 29, then rising gradually again to 37.4‰ at station 33.

3.3.4. Survey 4: 12 November (Figure 7b)

Profile station 1

Profile 1 was taken in weakly stratified NAW with no surface isothermal layer. Temperature ranged from 17.6-13.2°C falling from maximum (17.6°C) at 5m to 14.9°C at

40m, then more gradually to 13.5°C at 100m, reaching minimum (13.2°C) at, and below, 120m.

Chl F' ranged from <0.1-7.5 mg m^{-3}, rising sharply from 1.0 mg m^{-3} at 2-5m, to maximum (7.5mg m^{-3}) at 20m, then falling sharply to 0.9 mg m^{-3} at 40-50m, then falling further to <0.1 mg m^{-3} at, and below, 65m.

Phaeophytin a was not detectable throughout the water column (0-100m), indicating a healthy phytoplankton population. NO_3 ranged from 0.2-0.92 ppb, being minimum (0.2 ppb) at 0m and rising from 0.7 ppb at 20m to maximum (0.92ppb) at 55m, where Chl F' levels were highest, then falling to 0.72 ppb again at 100m. SiO_2 ranged from 4.4-10.0 ppb, increasing steadily from minimum (4.4 ppb) at 0m to maximum (10.0 ppb) at 100m. PO_4 ranged from 0.39-0.52 ppb, falling slightly from 0.4 ppb at 0m to 0.39 ppb (minimum) at 20m, then rising to maximum (0.52 ppb) at 55m (below the bulk of Chl F') before falling slightly to 0.51 ppb at 100m.

Profile station 2

Profile 2 was again in NAW. Temperature ranged from 17.8-13.2°C, being virtually isothermal to 25m then falling to 14.2°C at 65m, and remaining relatively constant from 65-90m, with a slight temperature inversion at around 80m, before falling to minimum (13.2°C) at, and below, 140m.

In vivo Chl F' ranged from <0.1-6.0 mg m^{-3}, rising from 1.8 mg m^{-3} at 1m to 5.0 mg m^{-3} at 10m, then falling to 3.0

mg m^{-3} at 15m before peaking again to 6.0 mg m^{-3} (maximum) at 25m (at the base of the isothermal layer) and falling to 0.5 mg m^{-3} at 50-65m, then falling gradually to minimum (<0.1 mg m^{-3}) at, and below, 80m. *In vitro* phaeophytin *a* ranged from 0.0 to 4.84 mg m^{-3}, being 1.67 mg m^{-3} at 0m, zero at 25 & 60m, and rising to 4.84 mg m^{-3} at 100m. NO_3 varied from 0.37-1.35 ppb, falling from 0.66 ppb at 0m to minimum (0.37 ppb) at 25-60m, below the isothermal layer, then rising to maximum (1.35 ppb) at 100m. SiO_2 ranged from 4.6-10.3 ppb rising steadily from minimum (4.6 ppb) at 0m to maximum (10.3 ppb) at 100m. PO_4 varied from 0.54-0.96 ppb, falling from maximum (0.96 ppb) at 0m to minimum (0.54 ppb) at the base of the isothermal layer (25m), then rising to 0.64 ppb at 60m before falling again to 0.59 ppb at 100m.

Profile station 3

Profile 3 showed no surface isothermal layer, and temperature ranged from 17.2-13.2°C, falling from maximum (17.2°C) at 5m to 15.9°C at 30m, then falling to minimum (13.2°C) at, and below, 140m, with slight temperature inversions (typical of a front) at 35m and 80m.

In vivo Chl F' ranged from <0.1 to 7.5 mg m^{-3}, peaking from 2.0 mg m^{-3} at 2m to maximum (7.5 mg m^{-3}) at 10m, falling sharply to 1.5 mg m^{-3} at 30-35m, then more gradually to minimum (<0.1 mg m^{-3}) at, and below, 70m. *In vitro* phaeophytin *a* ranged from 0.95 to 2.12 mg m^{-3}, falling from 2.12 mg m^{-3} at 0m to 0.95 mg m^{-3} at 10m, but

was not detectable at 30-100m. NO_3 varied between 0.5 and 1.57 ppb, rising from minimum (0.5 ppb) at 0m to 1.44 ppb at 10m, coincident with the chlorophyll peak, falling to 0.95 ppb at 30m, then rising to maximum (1.57 ppb) at 50m before falling again to 1.29 ppb at 100m. SiO_3 ranged from 4.2-10.9 ppb, rising slightly from minimum (4.2 ppb) at 0m to 4.4 ppb at 10m, then increasing steadily to maximum (10.9 ppb) at 100m. PO_4 ranged from 0.41-0.66 ppb, increasing gradually from minimum (0.41 ppb) at 0m to 0.63 ppb at 50m, and reaching maximum (0.66 ppb) at 100m.

Profile station 4

Profile 4 was taken in GW, showing a high surface temperature and a surface isothermal layer with a strong thermocline at 10-20m. Temperature ranged from 20.0-13.2°C, being virtually isothermal to 10m, and falling to 17.5°C between 10 & 20m, then decreasing to approximately 14.6°C at 70m, remaining relatively constant to 90m and falling gradually to minimum (13.2°C) at, and below, 140m.

In vivo Chl F' ranged from <0.1-6.0 mg m^{-3}, being <0.1 mg m^{-3} at 0-1.5m, increasing gradually to 2.8 mg m^{-3} at 20m, then sharply to maximum (6.0 mg m^{-3}) at 25m, with the bulk of the chlorophyll forming a sharp peak just below the thermocline at 25-30m, then falling sharply to 2.2 mg m^{-3} at 35m, and decreasing to minimum (<0.1 mg m^{-3}) at, and below, 70m. *In vitro* phaeophytin a ranged from 0-1.72 mg m^{-3}, rising from zero at 0m to maximum (1.72 mg m^{-3}) at 15m (where chlorophyll values were beginning to increase),

then falling to 0.43 at 25m and zero again at 80m. NO_3 ranged from 0.81-1.43 ppb, falling from maximum (1.43 ppb) at 0m to 1.25 ppb at 15m then gradually to minimum (0.81 ppb) at 160m. SiO_3 (4.4-11.8 ppb) rose from minimum (4.4 ppb) at 0-15m to 4.8 ppb at 25m (at the base of the thermocline, where chlorophyll values were highest), then increased steadily to 11.8 ppb (maximum) at 160m. PO_4 (0.52-0.76 ppb) fell from 0.66 ppb at 0m to minimum (0.52 ppb) at 25m (again, at the chlorophyll maximum), then rose to 0.72 ppb at 80m, and thence to maximum (0.76 ppb) at 160m.

Profile station 5

Profile 5 was again in GW, showing high SST and a strong isothermal layer. Temperature ranged from 20.3-13.2°C, being isothermal to 15m, with a strong thermocline between 15 & 30m (19.8 to 17.5°C), then falling gradually to minimum (13.2°C) at, and below, 160m.

In vivo Chl F' ranged from <0.1-1.0 mg m^{-3}, rising from minimum (<0.1 mg m^{-3}) at 1-15m to maximum (1.0 mg m^{-3}) at the thermocline (20-25m), then falling to minimum (<0.1 mg m^{-3}) again at, and below, 50m. Chlorophyll values were uniformly very low. *In vitro* phaeophytin *a* values were also very low, being detectable only at 15m (0.08 mg m^{-3}). NO_3 (0.81-1.19 ppb) fell from maximum (1.19 ppb) at 0m to minimum (0.81 ppb) at 15m at the top of the thermocline, rising slightly to 0.99 ppb at 90m. SiO_3 (4.7-9.8 ppb) fell from 5.8 ppb at 0m to minimum (4.7 ppb) at 15m,

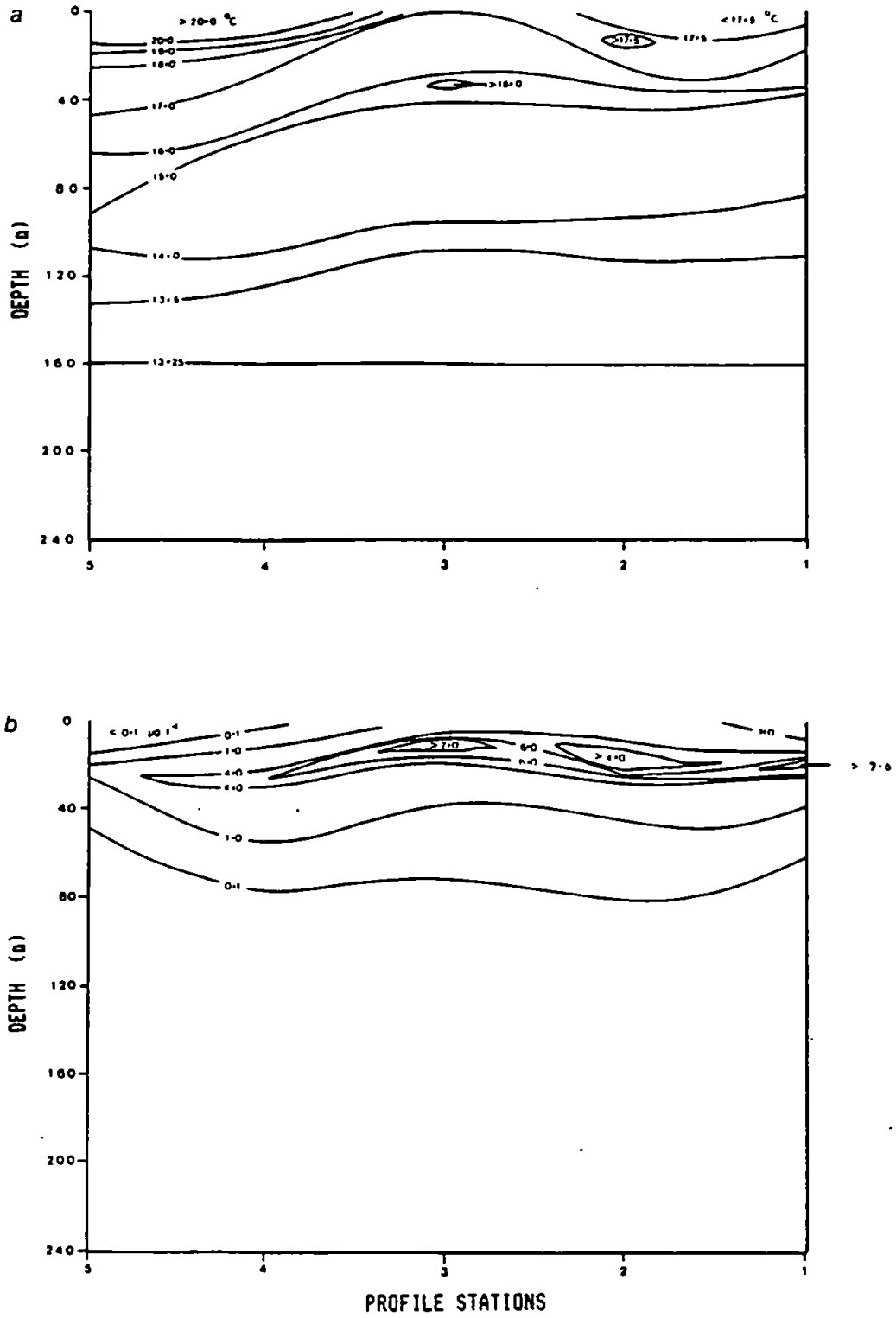


Figure 9. (a) temperature (°C), and (b) chlorophyll *a* (mg m^{-3}) distribution with depth across the front between NAW and GW, 12 November 1981.

remained constant to 90m, then rose to maximum (9.8 ppb) at 180m. PO_4 (0.35-0.55 ppb) rose from minimum (0.35 ppb) at 0m to 0.39 ppb at 90m, and increased to maximum (0.55 ppb) at 180m.

The distribution of temperature and *in vivo* chlorophyll *a* with depth for Profile Stations 1 to 5 are shown in Figure 9.

3.3.5. Satellite data

Atmospheric conditions were suitable for clear imaging by AVHRR (Advanced Very High Resolution Radiometry) satellite IR photographs from TIROS N-7 (Copyright of University of Dundee) on 7, 11 and 15 November 1981 (Plate 1), although these images were not available during the trials period.

On 7 November, at 1450 h, UV and IR photographs show the influx of NAW flows eastwards along the south coast of Spain and then southerly at 36°N, 4°W forming an anticyclonic gyre entrapping a warmer water mass. The gyre is approximately 150 km in diameter (east-west) and about 100 km in a north-south dimension, with temperature gradients across the front appearing strongest at the northern edge of the gyre.

The UV and IR photographs obtained at 1404 h on 11 November show that a significant change had occurred in the configuration of the gyre, and it had now assumed a

PLATE 1.

TIROS N-7 visible and infrared images of the Alboran Basin received and enhanced by the University of Dundee. (a) 7, (b) 11, (c) 15 November 1981.

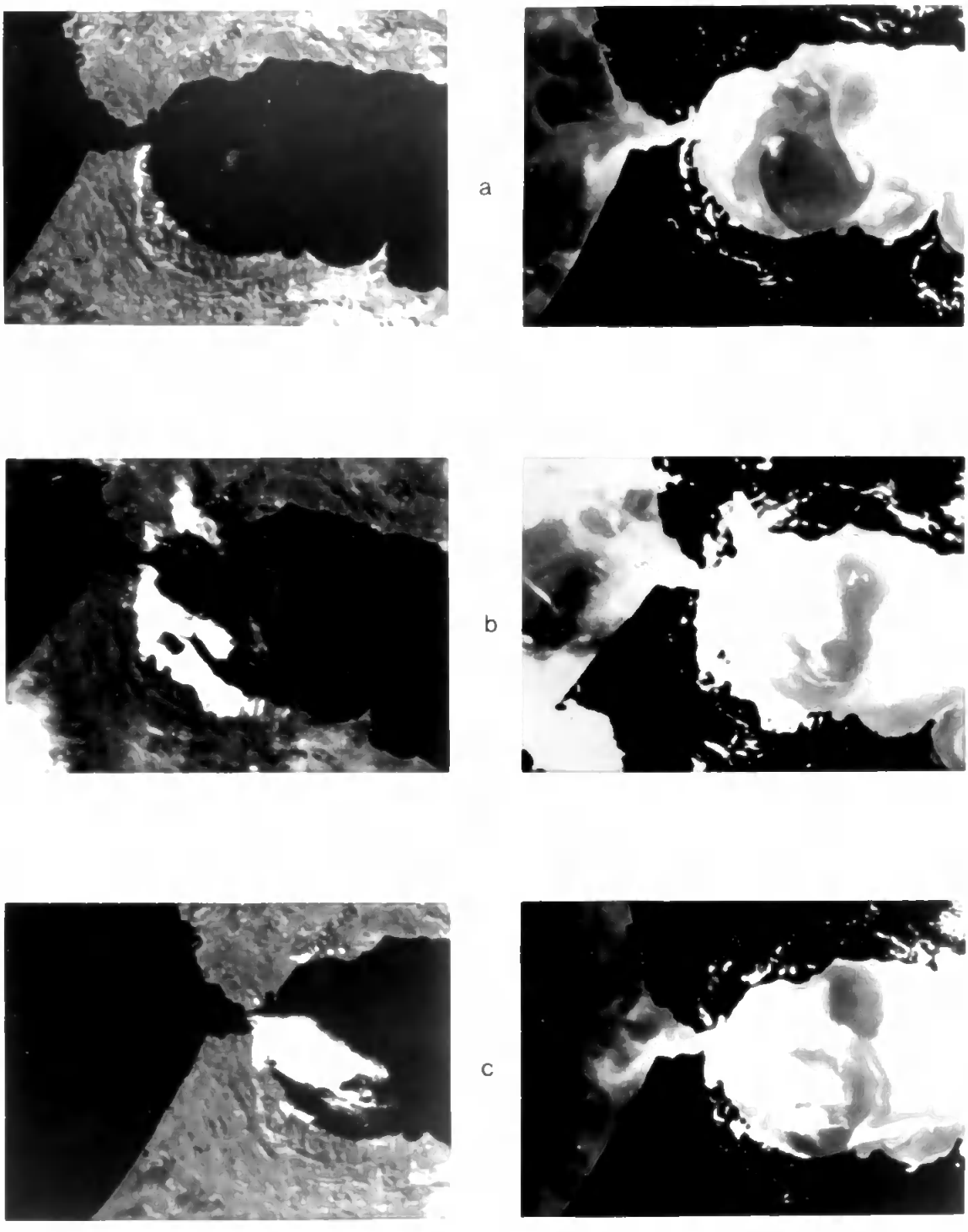


PLATE 1

dumb-bell shape. The eastern edge of the gyre had not markedly changed position, but the western edge had moved in an easterly direction, and at its narrowest the gyre was now only about 35 km wide.

Satellite photographs taken at 1459 h on 15 November show the main gyre has effectively split into 2 smaller gyres, the northern gyre having a diameter of about 60 km. Temperature gradients appear to be less distinct than those in the earlier satellite photographs.

3.4. DISCUSSION.

3.4.1. Initial location of the front

In the initial survey carried out on the 9-10 November 1981, a front between the in-flowing NAW and the warmer, more saline Alboran Basin Gyre was located at the north of the survey area between XBT stations 3 and 5 (Figure 5), SST rose from 19.0 to 20.0°C and salinity increased from 36.6 to 37.0‰ , with XBT number 4 showing the temperature inversion typical of frontal regions. Associated changes were also seen in Chl F, which varied from 44 to 60 tus between stations 2 and 4, then falling and remaining constant at 26-30 tus from stations 5 to 23.

This front was again located on the second transit, with SST falling gradually from 20.5°C at station 21 to 19.0°C at station 23, and salinity falling from 37.3‰ at station 21 to 36.7‰ at station 22. Chl F again showed

changes between the two water masses, being higher in NAW than in GW, but the increase in fluorescence occurred later than that of either temperature or salinity, rising steadily from 26 tus at station 22 to 55 tus at station 26.

At the south-eastern edge of the survey area SST indicated the presence of a second front, decreasing from 20.4°C at station 10 to 19.1°C at stations 13 to 15 inclusive, then increasing sharply again to 20.1°C at station 16. Salinities, however, indicated an intermediate water mass at 36.8‰ in the extreme south-east, increasing to 37.2‰ at station 16, and Chl F (30 tus) was typical of that found in GW. XBT profiles in this region confirmed the lower surface temperatures indicative of NAW, but also showed a shallow surface isothermal layer which was not evident in the profiles taken in the NAW at the north of the survey area. The development of this isothermal layer was interpreted as a consequence of surface heating of this NAW during its residence time in the Alboran Basin.

The change in SST at the south-east of the survey area was attributed to crossing a front between GW and NAW that is flowing south to form the eastern edge of the boundary of an anticyclonic gyre. Subsequent analysis of IR satellite data however, shows that the gyre was in the process of changing shape (Plate 1), and it is therefore more likely that the front detected by SST was that between the original, single gyre and the intrusion of NAW

which was to split the gyre by the 15th November, resulting in an anticyclonic gyre in the south of the Alboran Basin and a cyclonic gyre in the north.

3.4.2... Vertical distribution of temperature and Chl F across the front.

On 10 November, an attempt was made to obtain a series of vertical profiles across the well-defined front identified the previous day in the northwest of the survey area (Figure 5). Sea surface monitoring on this date, however, showed only NAW, with temperatures of 18.6-19.9°C, a salinity of 36.7‰, and Chl F values decreasing from 85 tus in the north to 40 tus in the south.

Profile 1 showed a surface isothermal layer to around 20m, with a strong thermocline at 18-23m and a temperature inversion (typical of frontal regions) at 60-70m. At Profile 2, SST was 0.3°C lower than at Profile 1, and the thermocline was less well-developed. Surface temperatures at Profile 3 were 0.1°C higher than at the previous profile station, and there was no well-defined thermocline, indicative of progressively more active mixing processes from north to south (this was supported by increases in nutrient levels north to south), with inflowing NAW losing momentum during its passage through the Alboran Basin, and stratification becoming more pronounced as a consequence of decreased mixing processes and

increased surface heating due to a longer residence time in the Alboran Basin.

Had the water structure been similar to that on the 9 November, the profiles would have ended in GW, which was not the case. In view of the fact that Profile 1 appeared to be frontal, with the temperature profile showing a typical temperature inversion, together with the higher Chl F values found in the north of the survey area, it was concluded that the gyre had moved in a north-easterly direction, and a further, more extensive survey was undertaken on the 11-12 November in order to re-locate the front.

3.4.3. Re-location of the front.

The front was again located on the 11 and 12 November, and had continued to move in an easterly direction. Confirmation of the movement of the frontal system as observed by the real-time monitoring of sea surface parameters was confirmed by subsequent analysis of AVHRR satellite IR photographs from TIROS N-7 taken on 30 October and 11 and 15 November 1981 (Plate 1).

XBT data for the 11 Nov (Appendix 1) show that stations 1 to 8 were in GW. The surface isothermal layer became less deep at station 7, becoming very shallow at station 8. Stations 9, 10 and 11 show the temperature inversion typical of frontal regions and indicate that the ship was either running parallel to the front or approaching it

obliquely, crossing it at right angles between stations 11 and 12. XBTs 30 to 35 inclusive, were taken in GW, crossing into NAW at station 36 and back into GW at station 44.

On the 12 November, a series of vertical profiles was made across the front (Figure 7b & 8). XBTs 1, 2A and 2B were taken in GW, and XBTs 3-10 in NAW (Appendix 1). Profile 1 was taken in weakly stratified NAW with no surface isothermal layer; surface chlorophyll was high (but less than at stations 2 and 3), with the main chlorophyll peak occurring at, and below, the weak thermocline.

Profile 2 was again in NAW, but isothermal to about 30m, with slightly higher surface temperature (possibly due to the effects of daytime surface heating); surface chlorophyll was higher than at station 1, with the greatest concentrations at, and above, the main thermocline, and just below the daily thermocline.

Profile 3 was very close to the front, showing the typical temperature inversion at 35-40m, with no surface isothermal layer; surface chlorophyll was high, with values peaking closer to the surface than at stations 1 and 2, the majority of the chlorophyll being above the warm water intrusion in the well-mixed region.

Profile 4 was taken in GW, showing increased surface temperatures and a surface isothermal layer with a strong thermocline at 15-20m. Surface chlorophyll was very low,

increasing at, and below, the secondary weaker thermocline.

Profile 5 was also in GW, and isothermal to about 20m. Chlorophyll levels throughout the water column were very low, with a slight increase just below the thermocline.

3.4.4. Correlation between temperature, salinity and Chl F across the front.

Although a degree of correlation was found between temperature and salinity in crossing the front between inflowing NAW and GW, the chlorophyll data showed no correlation with either temperature or salinity in crossing the front. This was despite the fact that both the NAW and the GW could both be characterized by typical Chl F values.

The overall results from the November 9 - 12 period indicated that the chlorophyll fluorescence response may precede both temperature and salinity responses, suggesting that the real-time monitoring of *in vivo* chlorophyll fluorescence levels might offer a potential "early-warning" of an approaching frontal system. It could also allow a course parallel to the front to be followed (by navigating along high or low fluorescence routes) without the necessity of crossing the front in order to locate its position.

The discrete samples taken for pigment analysis showed a low correlation between chlorophyll *a*

concentration and *in vivo* fluorescence yield. This could have been due to a number of factors, such as differences in species composition between the two water masses, diurnal variation in photosynthetic processes, or to nutrient stresses.

This low correlation persisted when the data were broken down into either different water masses or into day-night subgroups. Since insufficient samples were taken to divide the data into day-night subgroups within the 2 different water masses, the data must, therefore, be regarded as qualitative rather than quantitative. However, it would appear that it is the relative values of chlorophyll which are critical for this study, not absolute values.

3.4.5. Satellite Imagery

In view of the failure on the 10 November to locate the front identified the previous day in the northwest of the survey area, it was concluded that the gyre must have moved in a north-easterly direction. Subsequent analysis of satellite IR imagery (Plate 1), however, indicated that not only had the gyre shifted position, but it was in the process of changing shape.

UV and IR images at 1450 h, 7 November, show the influx of NAW flowing eastwards along the south coast of Spain and then southerly at 36°N, 4°W forming an anticyclonic gyre entrapping a warmer water mass. The gyre is

approximately 150 km in diameter (east-west) and about 100 km in a north-south dimension. By 1404 h, 11 November (Plate 1), however, a significant change had occured in the configuration of the gyre, and it had now assumed a dumb-bell shape, being now only about 35 km wide at its narrowest point.

Profiles 1-3 (10 Nov) had been taken in the tongue of NAW which was to split the gyre into two, with Profile 1 being at the boundary of what was to become the northern gyre. Had the survey continued in a southerly direction, then the tongue of NAW would have been crossed, and gyre water again encountered.

The satellite photographs taken at 1459 h on the 15 November show that the main gyre has effectively split into two smaller gyres, the northern one having a diameter of about 60 km. Temperature gradients apppear to be less distinct than those in the earlier satellite photographs.

3.4.6. The Alboran Basin gyre - a seasonal anomaly?

Ovchinnikov *et al* (1976) have argued that this gyre is not a persistent feature of the Alboran Basin, but an anomaly created by unusual northwest winds during particular summers. Other workers (Donguy, 1962; Cheney, 1977, 1978; Cheney & Doblar, 1982; Grousson & Faroux, 1963; Lacombe *et al*, 1964; Stevenson, 1977) contend that it is a persistent feature, at least during the late spring and summer, regardless of the prevailing wind

direction. Data for other seasons is limited, but those that do exist (Cheney, 1978; Lucaya & DeCastillejo, 1972) indicate that the gyre is a normal feature of the circulation pattern and persists throughout the year, along with a series of alternating cyclonic and anticyclonic gyres to the east of the main anticyclonic gyre. The present study has shown this gyre was detectable in November 1981, and therefore does not only occur in the spring and summer months. It has also been detected in October by Cheney & Doblar (1982), who also recorded a distinct shift in the position of the gyre when comparing an initial aerial survey with shipboard measurements made over a 10 day period.

Although the gyre is, therefore, not a seasonal anomaly, as suggested by Ovchinnikov *et al.* (1976), it is known that local wind stress plays an important role in the transport of Atlantic water through the Straits of Gibraltar into the Alboran Basin (Lacombe, 1971), with west winds causing an increase in surface transport, and easterlies a decrease. This, together with the effect of atmospheric pressure variations over the Mediterranean (Lacombe, 1961; Crepon, 1965) is probably responsible for the observed shift in position of the gyre, and the splitting of the main anticyclonic gyre into the two smaller ones.

SECTION 4.

4. SEASONAL BASELINES OF TEMPERATURE, SALINITY AND CHL F AROUND THE UNITED KINGDOM.

4. SEASONAL BASELINES OF TEMPERATURE, SALINITY AND CHL F AROUND THE UNITED KINGDOM.

4.1. INTRODUCTION

Most of the earlier studies of fronts (Cromwell & Reid, 1956; Knauss, 1957; Voorhis & Hersey, 1964; Bang, 1973) were concerned primarily with the physical description and dynamics of frontal systems, whilst their biological and chemical features received much less attention. This situation began to change in the mid-1970s, with the shelf sea fronts around the UK beginning to attract investigation.

High chlorphyll levels have frequently been reported at these frontal regions (Pingree *et.al.*, 1978; Savidge, 1976; Simpson *et.al.*, 1979). It was thought that these bands of high chlorophyll were probably transient features, as increased phytoplankton production would lead to increased grazing pressure by zooplankton, and a consequent diminution of the phytoplankton population.

The results of the survey carried out in the Alboran Basin in November 1981 (Section 3) showed that changes in chlorophyll levels also occured in the vicinity of a deep-sea front, and indicated that these changes may occur in advance of changes in temperature. However, it is possible that the changes in Chl F which were seen across the front between NAW and GW during this period were also

a transient feature, since no historical data on chlorophyll distribution in the Alboran Basin were available for comparison.

In June 1982, AMTE (Admiralty Marine Technology Establishment) Portsmouth were invited to participate in a survey of the Ushant front (AUWE Trial 611/81), in order to provide biological and physical oceanographic measurements in support of other aspects of the trials programme (Aiken & Taylor, 1984).

The results of the AMTE work demonstrated that changes in Chl F also occurred in advance of temperature and salinity at a shelf sea front, with the changes observed in Chl F across the front occurring up to 4 miles in advance of temperature and salinity changes (Jackson & Hughes, 1984). This suggested the possibility that high chlorophyll levels were not, after all, a transient feature of frontal systems. If this were indeed the case, then the potential of using chlorophyll measurements as a detection method would be enhanced.

Although the distribution of chlorophyll *a* at shelf sea fronts has attracted much attention, studies have been mostly confined to the summer months, when stratification is most pronounced. No studies have been made of the seasonal distribution of chlorophyll around the UK.

A series of surveys was therefore undertaken in order investigate whether changes in Chl F were consistently associated with temperature gradients in the shelf seas around the UK, and to establish seasonal baselines of temperature, salinity and Chl F.

These surveys involved the continuous monitoring of temperature, salinity and Chl F at 3m around the UK, using ships of opportunity, for the period September 1982 to August 1983. Concentrations of chlorophylls *a*, *b*, *c*, and phaeophytin *a* are presented in detail (for reference) only for November 1982 and June 1983, since the present study was concerned with relative, not absolute, changes in chlorophyll levels.

4.2. STUDY AREA

All surveys were conducted along one or more of the following legs (Figure 10):

(a) Portmouth to Rosyth

(b) Rosyth to Milford Haven

(c) Milford Haven to Plymouth

(d) Plymouth to Portsmouth

(e) Guernsey to Plymouth to the Clyde

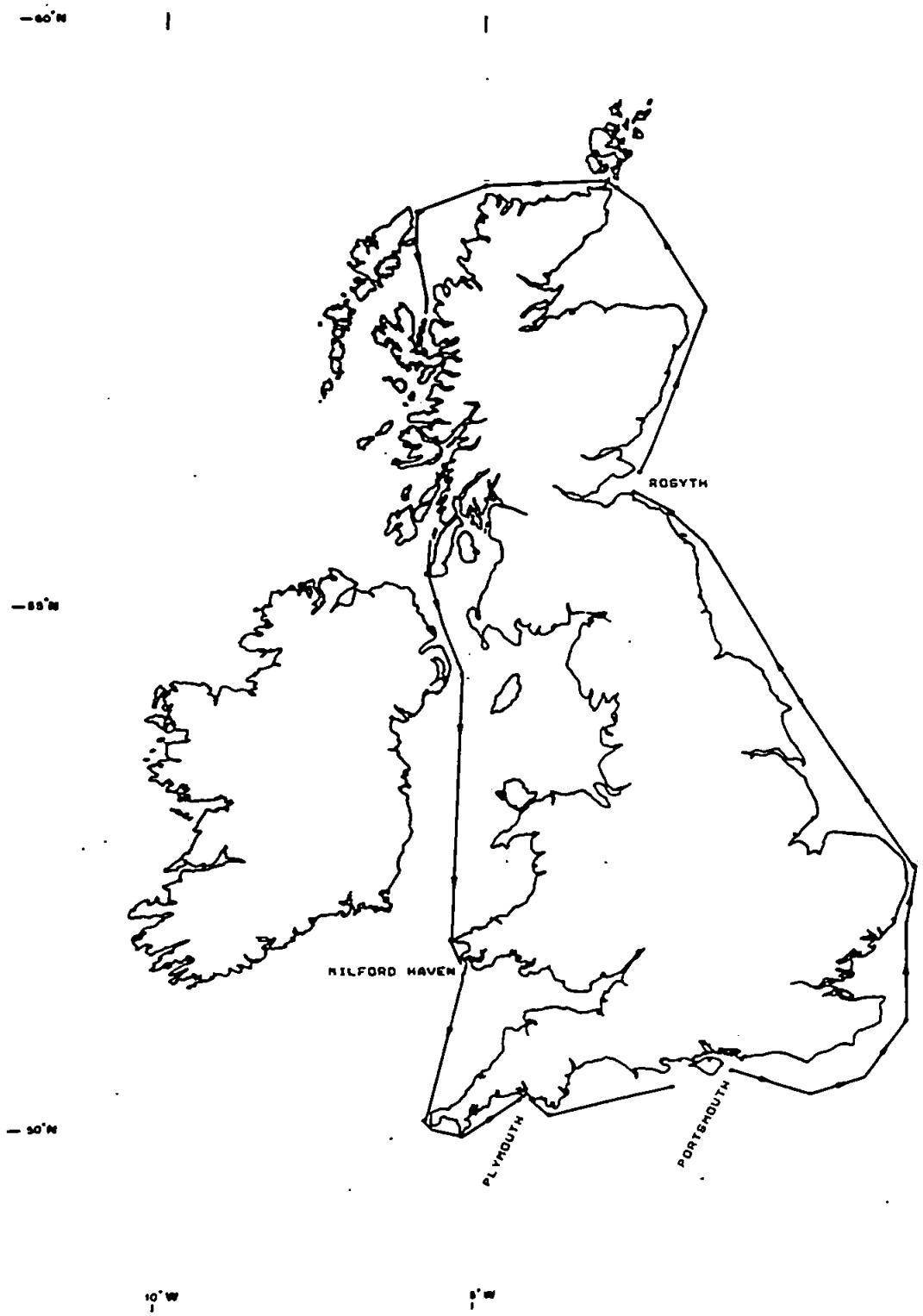


Figure 10.
Sampling transects for the period September 1982 to August 1983

4.3. SEPTEMBER 1982

4.3.1. Guernsey to the Clyde

Figure 11 shows the distribution of temperature, conductivity, Chl F and pH between Guernsey and Plymouth (0630-1400h 9 Sept), and between Plymouth and the Clyde (1700h 9 Sept. - 1745h 10 Sept.).

Temperature varied from 14.1 to 18.0°C. Fronts clearly indicated were (1) between the Lizard and the Scilly Isles (2130h 9 September); (2) Celtic Sea front (2300h 9 September); (3) Irish Sea front (1100h 10 September).

Calibration problems were encountered with the Partech TSD-81, which registered salinity as varying from 35.0 to 39.6‰, and havingan inverse relationship with temperature between Guernsey and Plymouth, and then broadly mirroring the temperature profile between Plymouth and the Clyde.

Chl F varied from 50 to 200 tus, with the highest values being associated with regions of sharp temperature change.

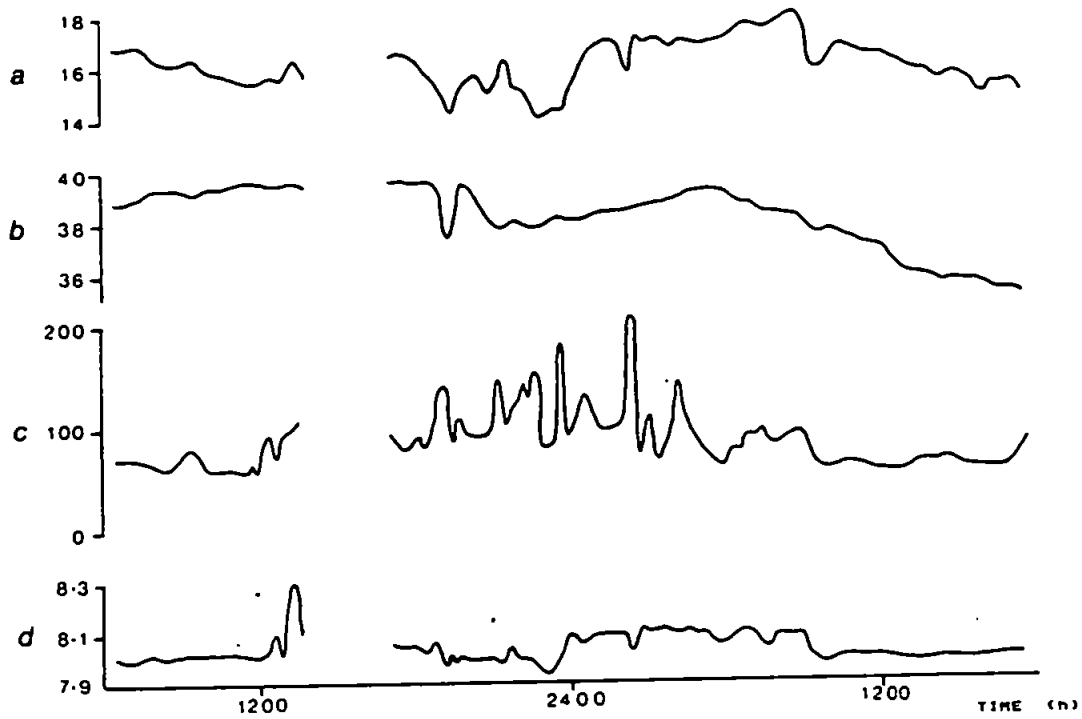


Figure 11. September 1982. Guernsey to Plymouth: 0630-1400h 9 Sept., Plymouth to the Clyde: 1700h 9 Sept - 1745h 10 Sept. Distribution of (a) temperature (°C), (b) conductivity, (c) Chl F (tus) and (d) pH at 3m.

4.4. NOVEMBER/DECEMBER 1982

This survey was carried out in two legs:

(1). Portsmouth to Rosyth, 29-30 November

(2). Rosyth to Milford Haven, 3-5 December

4.4.1. Portsmouth to Rosyth (Figures 12 & 13)

Temperature ranged from 6.0 to 11.4°C, being highest in the south (>10.0°C), then dropping to 7-8°C at about 51°N, and remaining at around this level before falling to minimum on approaching Rosyth.

Salinity varied from 33.0 to 34.4‰, showing a strong positive correlation with temperature.

Chl F varied from 3 to 13 tus, with the highest values (>8 tus) again being associated with the region of sharpest temperature change.

pH varied from 8.58 to 9.00 units, falling from maximum to minimum along the temperature gradient at 51°N, where Chl F values were increasing.

Chlorophyll *a* ranged from 0.2 to 1.5 mg m^{-3}, chlorophyll *b* from 0.0 to 0.3 mg m^{-3}, chlorophyll *c* from 0.0 to 0.3 mg m^{-3}, and phaeophytin *a* from 0.0 to 1.4 mg m^{-3}.

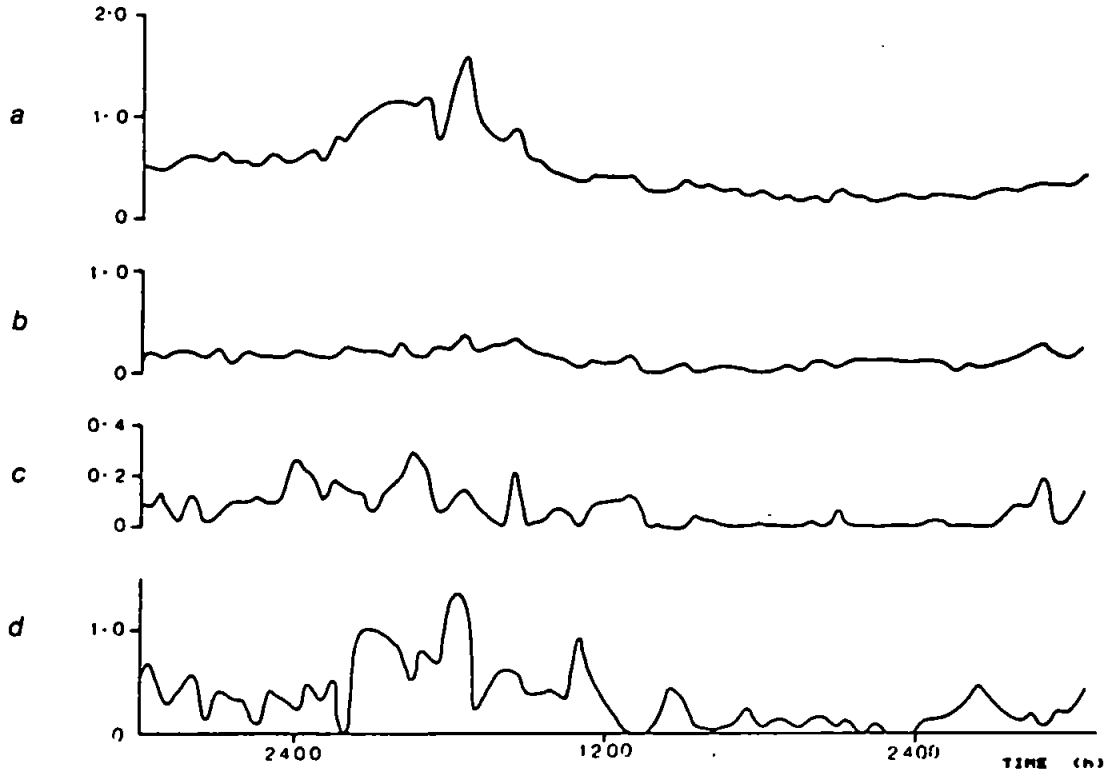


Figure 12. November 1982, Portsmouth to Rosyth: 1800h 29 Nov - 0630h 1 Dec. Distribution of (a) temperature (°C), (b) salinity (‰), (c) Chl F (tus) and (d) pH at 3m.

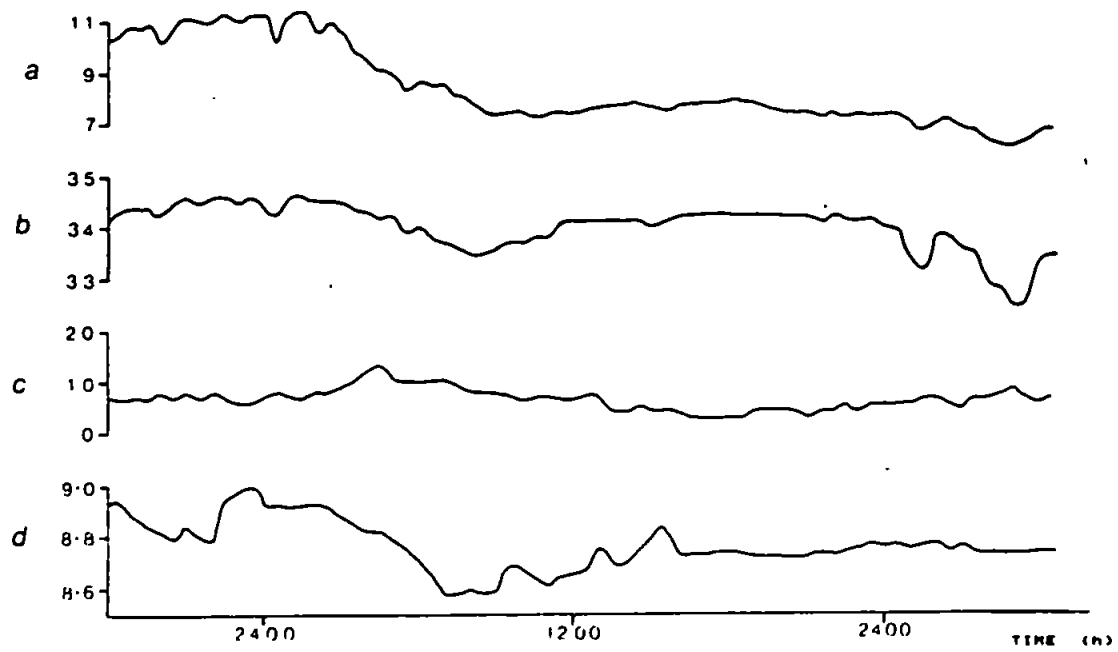


Figure 13. November 1982, Portsmouth to Rosyth: 1800h 29 Nov - 0630h 1 Dec. Distribution of (a) chlorophyll *a*, (b) chlorophyll *b*, (c) chlorophyll *c* and (d) phaeophytin *a* (mg m^{-3}) at 3m.

4.4.2. Rosyth to Milford Haven (Figures 14 & 15)

Temperature ranged from 8.0 to 10.5°C, showing a more or less steady increase along the transect.

Salinity ranged from 32.5 to 34.5‰, with the minimum values occuring between 56 and 57°N off the western Scottish coast..

Chl F varied from 0.5 to 7 tus, being highest around Rosyth on the east coast.

Chlorophyll *a* varied from 0.0 to 0.5 mg m^{-3}, with one anomalous peak at 1000 h on 4 December. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.0-1.0, 0.0-0.4 and 0.0-1.0 mg m^{-3} respectively.

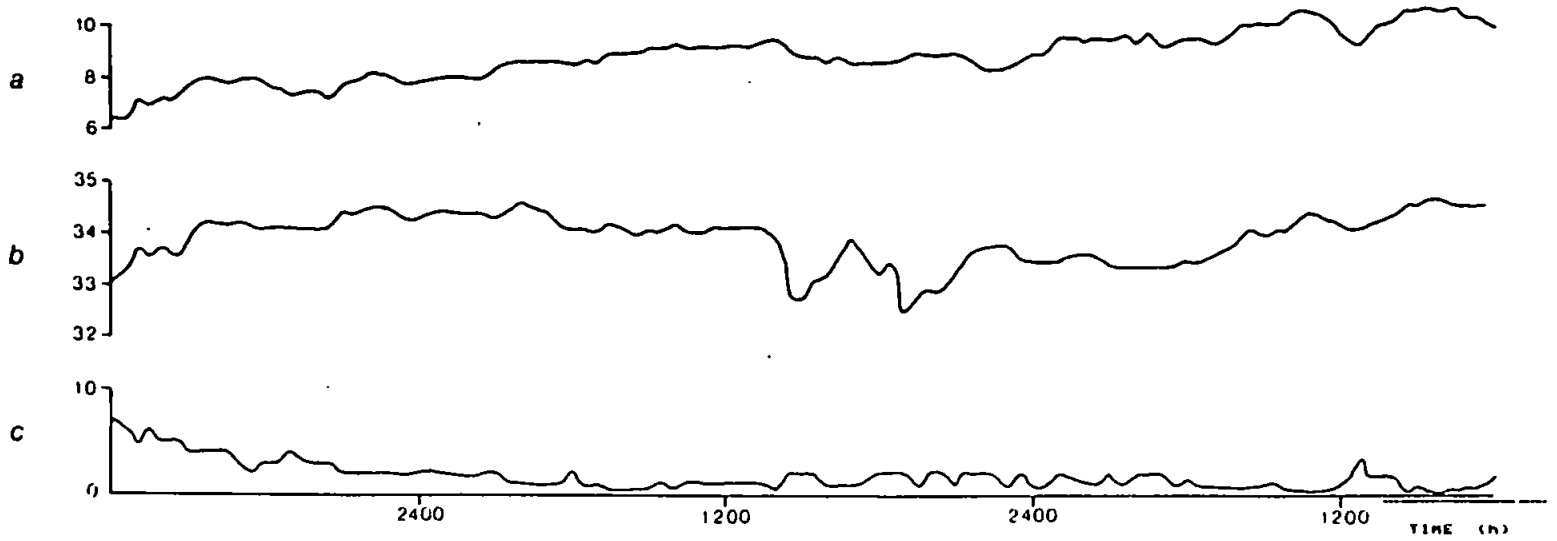


Figure 14. December 1982, Rosyth to Milford Haven: 1200h 3 Dec. - 1800h 5 Dec. Distribution of (a) temperature (°C), (b) salinity (‰) and (c) Chl F (tus) at 3m.

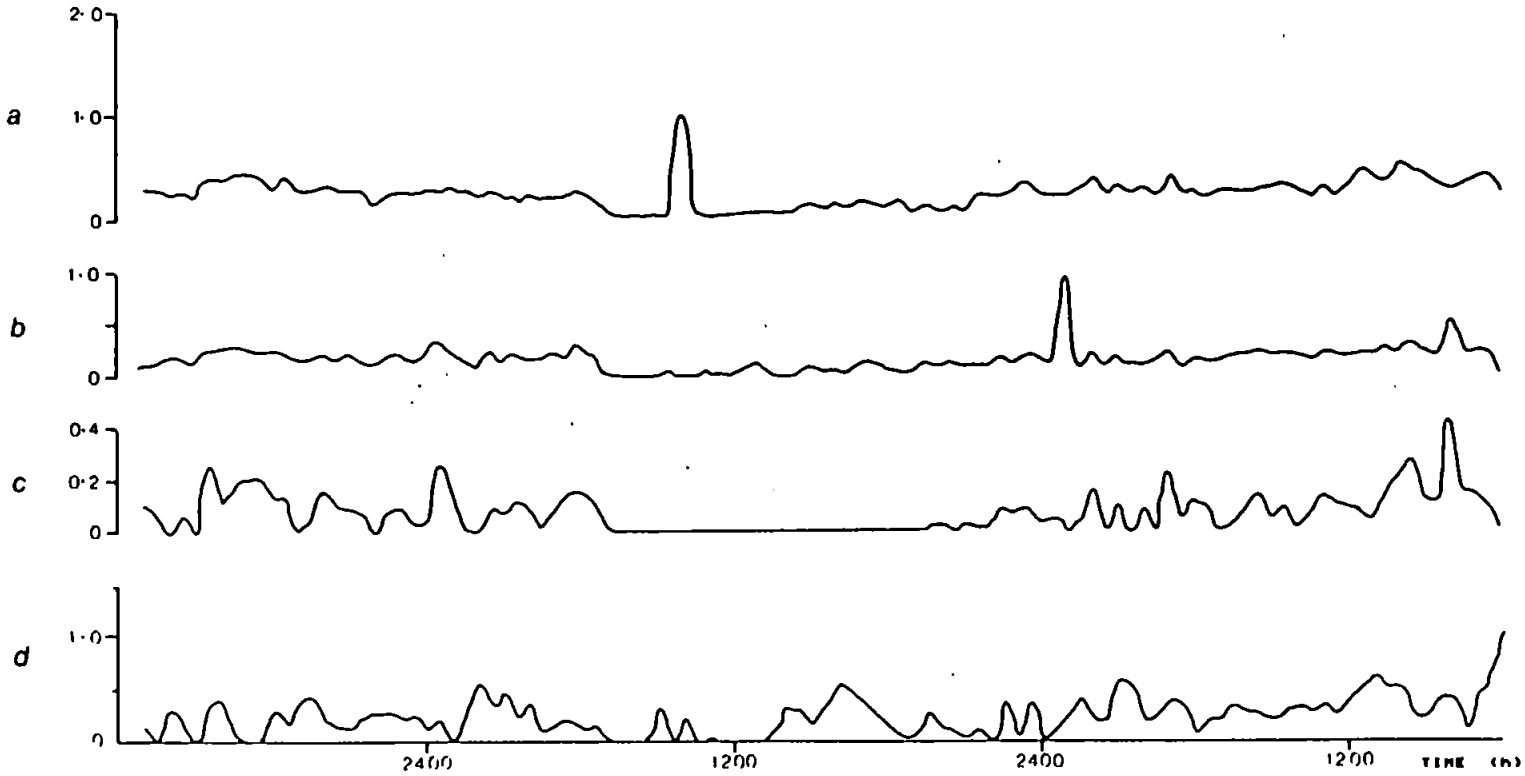


Figure 15. December 1982, Rosyth to Milford Haven: 1200h 3 Dec. - 1800h 5 Dec. Distribution of (a) chlorophyll *a*, (b) chlorophyll *b*, (c) chlorophyll *c* and (d) phaeophytin *a* (mg m^{-3}) at 3m.

4.5. APRIL 1983

This survey was carried out in 3 legs:

(1). Portsmouth to Milford Haven, 8-9 April.

(2). Milford Haven to Rosyth, 12-13 April.

(3). Rosyth to Portsmouth, 13-15 April.

4.5.1. Portsmouth to Milford Haven (Figure 16)

Temperature ranged from 8.0 to 9.6°C, increasing from minimum values at Portsmouth to around 9.0°C at 2°W (2130 h), and remaining at around this value until dropping to minimum again on approaching Milford Haven.

Salinity ranged from 32.0 to 34.4‰, remaining relatively steady at around 34.0‰, then dropping to minimum on approaching Milford Haven.

Chl F ranged from 6 to 60 tus, varying from between 6 to 16 tus for most of the transect, and peaking to maximum (60 tus) at 0800 h on 9 April, co-incident with the drop in both temperature and salinity on approaching Milford Haven.

Chlorophyll *a* varied from 0.21 to 3.44 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.08-1.12, 0.00-0.78 and 0.00-1.66 mg m^{-3} respectively.

4.5.2. Milford Haven to Glen Mullen (Figure 16)

Temperature ranged from 7.5 to 8.4°C, being fairly constant at around 8°C from 0830 to 2100 h, 12 April, then

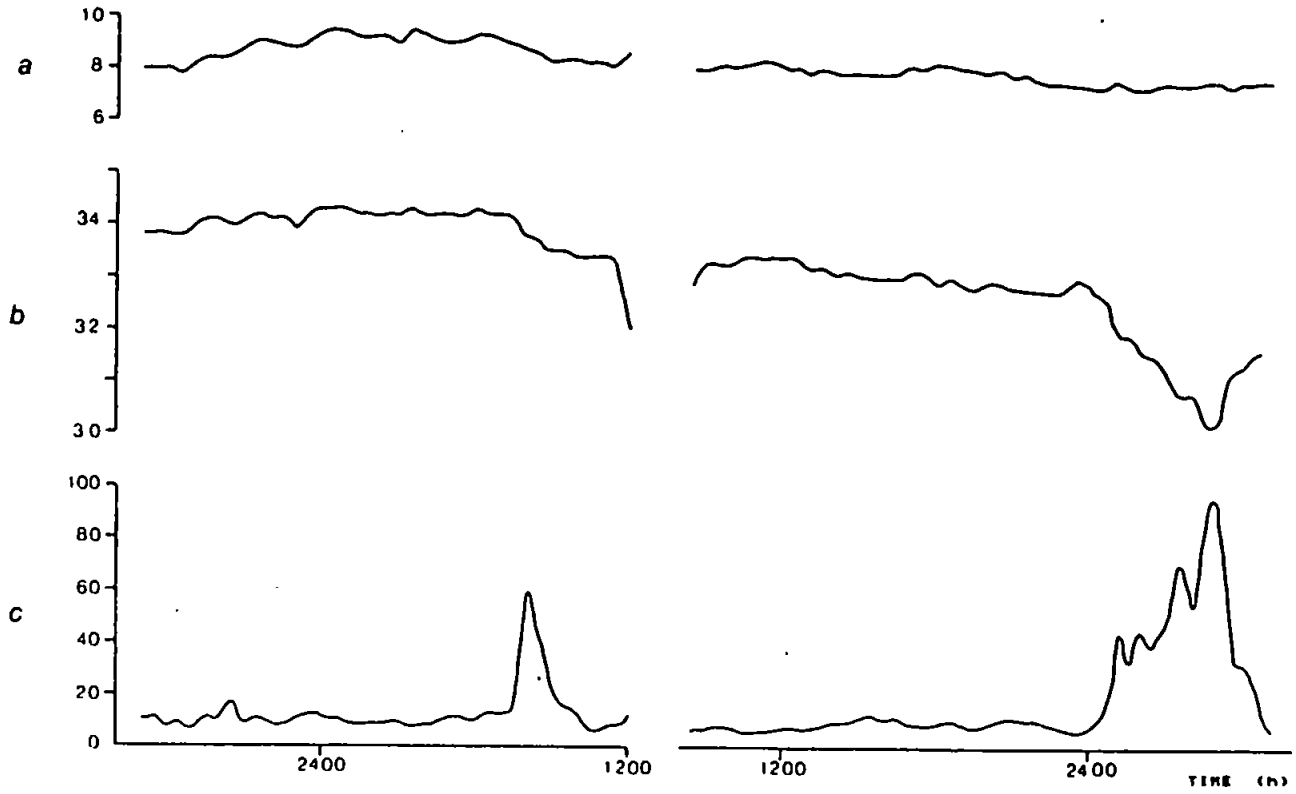


Figure 16. April 1983. Portsmouth to Milford Haven: 1700h 8 April - 1200h 9 April; Milford Haven to Glen Mullen: 0830h 12 April- 0700h 13 April. Distribution of (a) temperature (°C), (b) salinity (‰), and (c) Chl F (tus) at 3m.

falling to around 7.5°C from 2230 h to the end of the transect.

Salinity ranged from 30.2 to 33.4‰, falling steadily to 33.0‰ at around 2400h, then dropping sharply to minimum on approaching Glen Mullen.

Chl F ranged from 6 to 94 tus, being fairly constant at around 10 tus until 2400 h, when values rose sharply to maximum, co-incident with the fall in salinity.

Chlorophyll *a* varied from 0.51 to 18.21 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.10-1.8, 0.00-3.35 and 0.0-4.36 mg m^{-3} respectively.

4.5.3. Glen Mullen to Portsmouth (Figure 17)

Temperature ranged from 7.4 to 9.8°C, remaining below 8°C from 1700 h 13 April to 1130 h 14 April, then increasing steadily to maximum at 1600h 14 April. Temperature dropped again to around 8°C on approaching Portsmouth.

Salinity ranged from 30.2 to 34.5‰, being lowest at Glen Mullen, then increasing to ≈ 33.0‰ at 2330h 13 April and remaining at around this level to 1600h 14 April, when it increased to ≈ 34.0‰.

Chl F ranged from 5 to 138 tus, with maximum values at the start of the transect (1700-2200h) at Glen Mullen, co-incident with the lowest salinity levels. Another peak, again associated with temperature and salinity changes, was evident at 1700h 14 April.

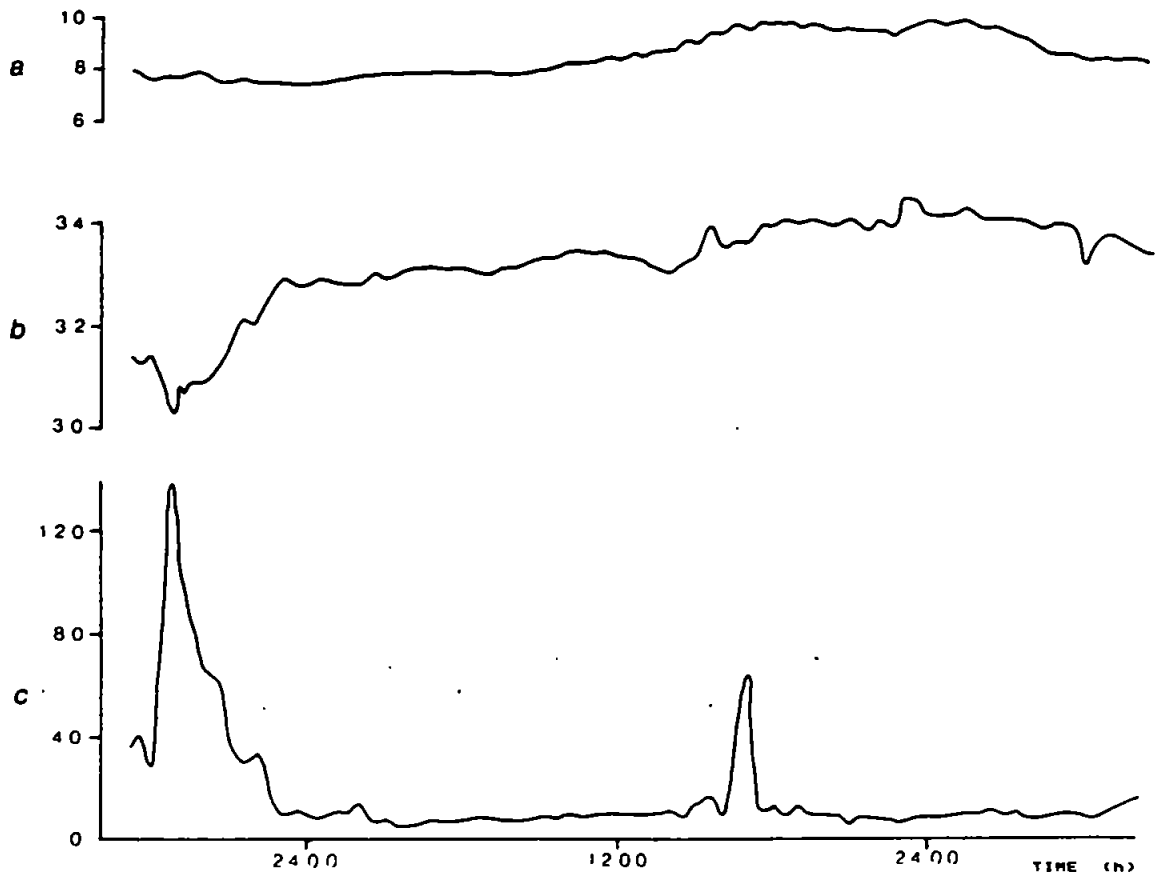


Figure 17. April 1983. Glen Mullen to Portsmouth: 1700h 13 April - 0830h 15 April. Distribution of (a) temperature (°C), (b) salinity (‰), and (c) Chl F (tus) at 3m.

Chlorophyll *a* varied from 0.04 to 20.82 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.00-2.26, 0.00-3.78 and 0.00-17.28 mg m^{-3} respectively.

4.6. JUNE 1983

Portsmouth to Rosyth (Figures 18 & 19)

Temperature ranged from 10.6 to 16.1°C, dropping sharply from maximum (16.1°C) to 13.6°C at the start of the transect, then rising to ≈14.0°C at 1830h 27 June. Temperature remained at around this level until 0800h 28 June, when it dropped steadily to 10.8°C at 1430h 28 June, before increasing again to 13.3°C at 1930h, then dropping steadily to minimum (10.6°C) at Rosyth.

Salinity ranged from 30.5 to 33.1‰, being >32.0‰ from 1600-2400h 27 June and from 1830-2230h 28 June.

Chl F ranged from 6 to 88 tus, being below 25 tus along most of the transect, but with peaks at 0600-0930h, 1300-1330h and 1730-1800h 28 June.

pH ranged from 8.1 to 8.5 units, being fairly steady at minimum from 1600h 27 June to 0200h 28 June. pH levels then peaked to maximum at 0700h, co-incident with the large peak in Chl F, before decreasing to 8.2 at 1030h. From 1230h 28 June to 0200h 29 June pH varied between 8.3 and 8.4.

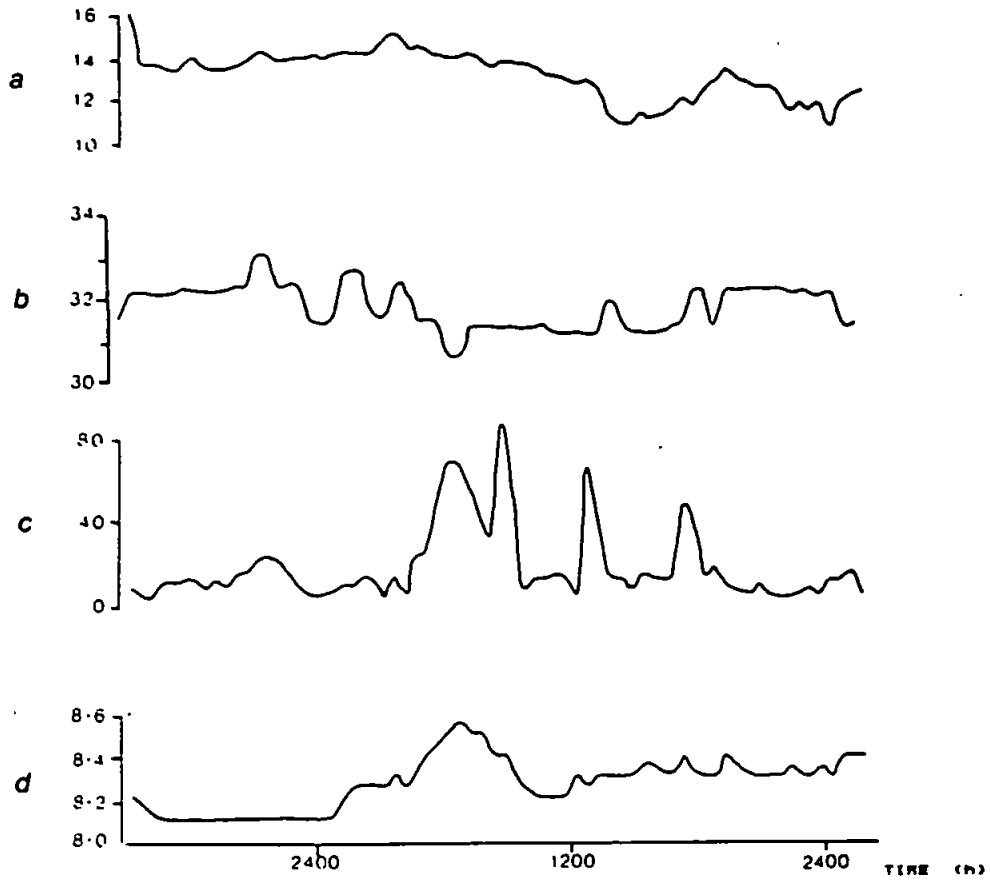


Figure 18. June 1983. Portsmouth to Rosyth: 1500h 27 June - 0200h 29 June. Distribution of (a) temperature (°C), (b) salinity (‰), (c) Chl F (tus) and (d) pH at 3m.

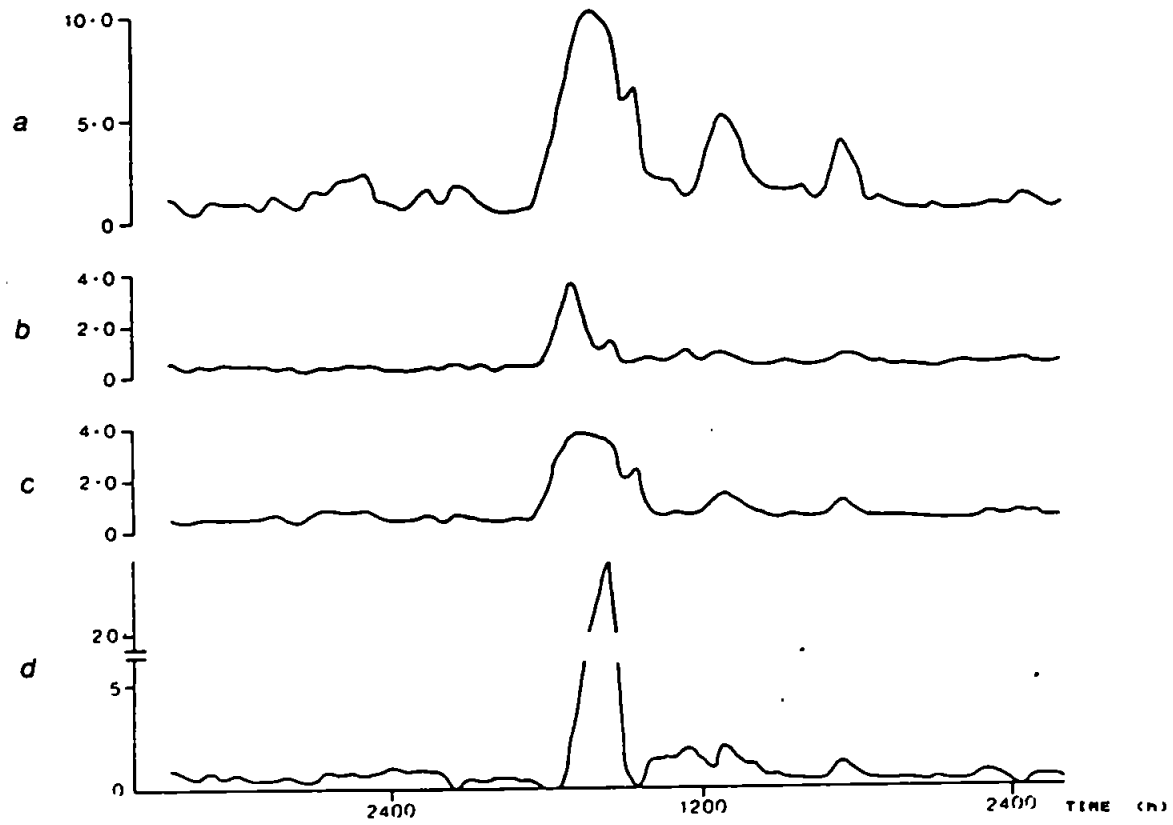


Figure 19. June 1983. Portsmouth to Rosyth: 1500h 27 June - 0200h 29 June. Distribution of (a) chlorophyll *a*, (b) chlorophyll *b*, (c) chlorophyll *c* and (d) phaeophytin *a* (mg m^{-3}) at 3m.

Chlorophyll *a* varied from 0.20 to 10.00 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.00-4.00, 0.00-4.00 and 0.00-22.80 mg m^{-3} respectively.

4.7. JULY 1983

4.7.1. Rosyth to Milford Haven (1-4 July)

Temperature, salinity, Chl F and pH at 3m for the period 1600h 1 July to 0700h 4 July are shown in Figure 20.

Temperature ranged from 10.5 to 13.1°C, showing many fluctuations, but with values generally being higher in the latter part of the transect.

Salinity varied from 32.0 to 34.0‰ and, like temperature, fluctuated markedly along the transect.

Chl F ranged from 5 to 30 tus, with changes in Chl F again being associated with temperature gradients. pH ranged from 8.2 to 8.4 units.

Chlorophyll *a* varied from 0.49 to 2.71 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.00-2.43, 0.00-1.10 and 0.00-4.52 mg m^{-3} respectively.

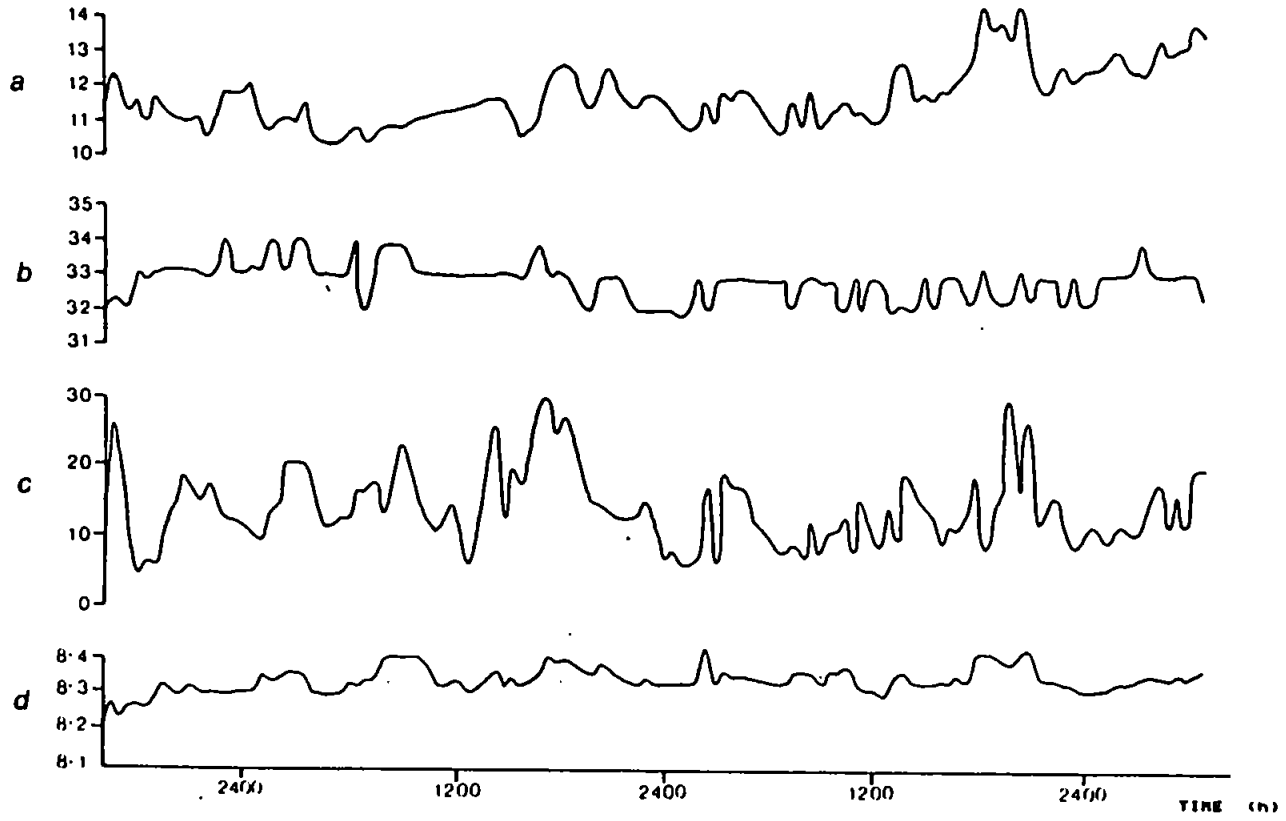


Figure 20. July 1983. Rosyth to Milford Haven: 1600h 1 July - 0700h 4 July. Distribution of (a) temperature (°C), (b) salinity (‰), (c) Chl F (tus) and (d) pH at 3m.

4.7.2. Milford Haven to Plymouth (6-7 July)

Temperature, salinity, Chl F and pH at 3m for the period 1700h 6 July to 0700h 7 July are shown in Figure 21.

Temperature ranged from 13.6 to 18.0°C, rising rapidly from minimum at 1700h to maximum at 1930h 6 July. The Scilly front is clearly identifiable at around 2400h.

Salinity ranged from 31.7 to 34.3‰, again showing many fluctuation along the transect.

Chl F ranged from 2 to 16 tus, with peaks at 1700h, 2300h 6 July, and 0700h 7 July, co-incident with the sharpest temperature gradients.

pH ranged from 8.2 to 8.4. Chlorophyll *a* varied from 0.31 to 2.36 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.20-0.58, 0.22-0.79 and 0.00-0.77 mg m^{-3} respectively.

4.7.3. Plymouth to Portsmouth (7-8 July)

Temperature, salinity, Chl F and pH at 3m for the period 2100h 7 July to 0300h 8 July are shown in Figure 21.

Temperature ranged from 14.7 to 17.7°C, with a sharp temperature gradient at 2400h 7 July to 0130h 8 July.

Salinity ranged from 32.5 to 33.2‰, showing an inverse relationship with temperature.

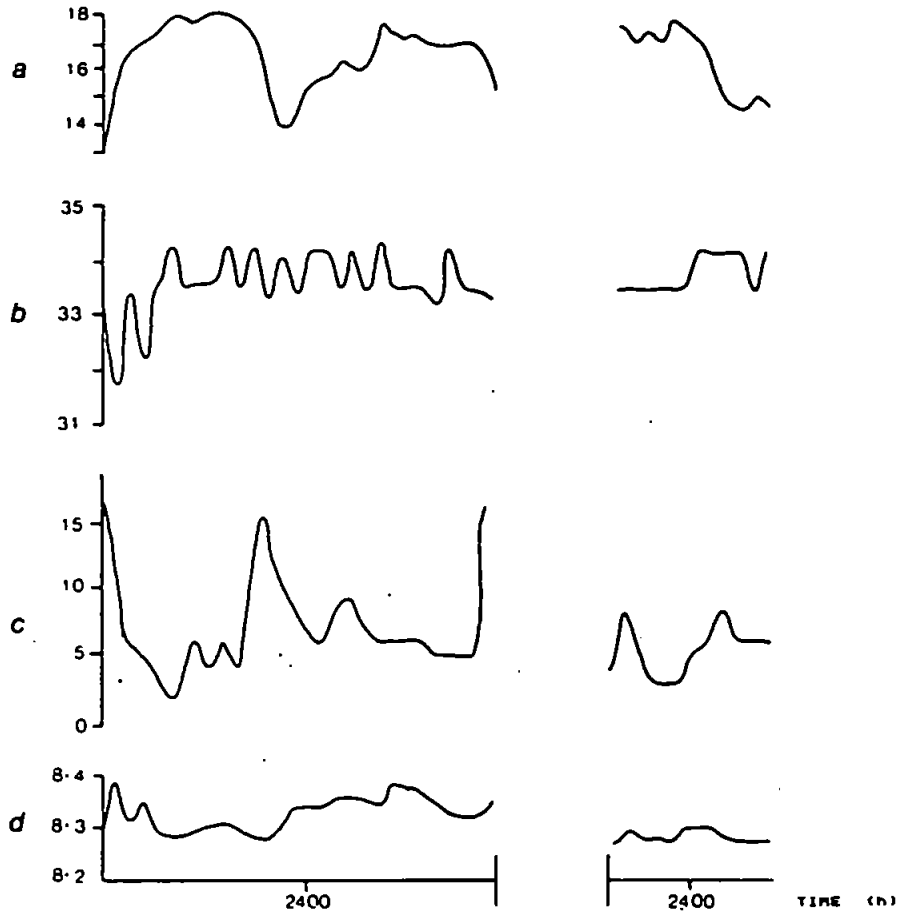


Figure 21. July 1983. Milford Haven to Plymouth: 1700h 6 July - 0700h 7 July. Plymouth to Portsmouth: 2100h 7 July - 0300h 8 July. Distribution of (a) temperature (°C), (b) salinity (‰), (c) Chl F (tus) and (d) pH at 3m.

Chl F ranged from 4 to 8 tus (peaking at temperature gradients, even at this low level), and pH ranged from 8.2 to 8.3.

Chlorophyll *a* varied from 0.36 to 0.89 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.24-0.37, 0.28-0.43 and 0.00-0.53 mg m^{-3} respectively.

4.7.4. Portsmouth to Milford Haven (11-12, 17-18 July)

Figure 22 shows the distribution of temperature, salinity, Chl F and pH at 3m from Portsmouth to Milford Haven (1800h 11 July - 1030h 12 July), and for the return transect, Milford Haven to Portsmouth (1900h 17 July - 0700h 18 July).

Temperature ranged from 13.8 to 19.8°C on the first transect, and from 14.2 to 21.9°C on the return leg. The Ushant front and the Scilly front were both detected on the first transect (2300h 11 July, 0500h 12 July). The Scilly front was also detected on the return leg (2300h 17 July), but on this transect the Ushant front was skirted, not crossed (0330h 18 July).

Chl F ranged from 2 to 21 tus on the 11-12 July, with peaks associated with the sharpest temperature gradients. On the return leg (17-18 July), Chl F ranged from 2 to 52 tus, with peaks again being associated with the temperature gradient.

pH ranged from 8.24 to 8.92 on the 11-12 July with three major peaks at 0030h, 0330h and 0600h on 12 July.

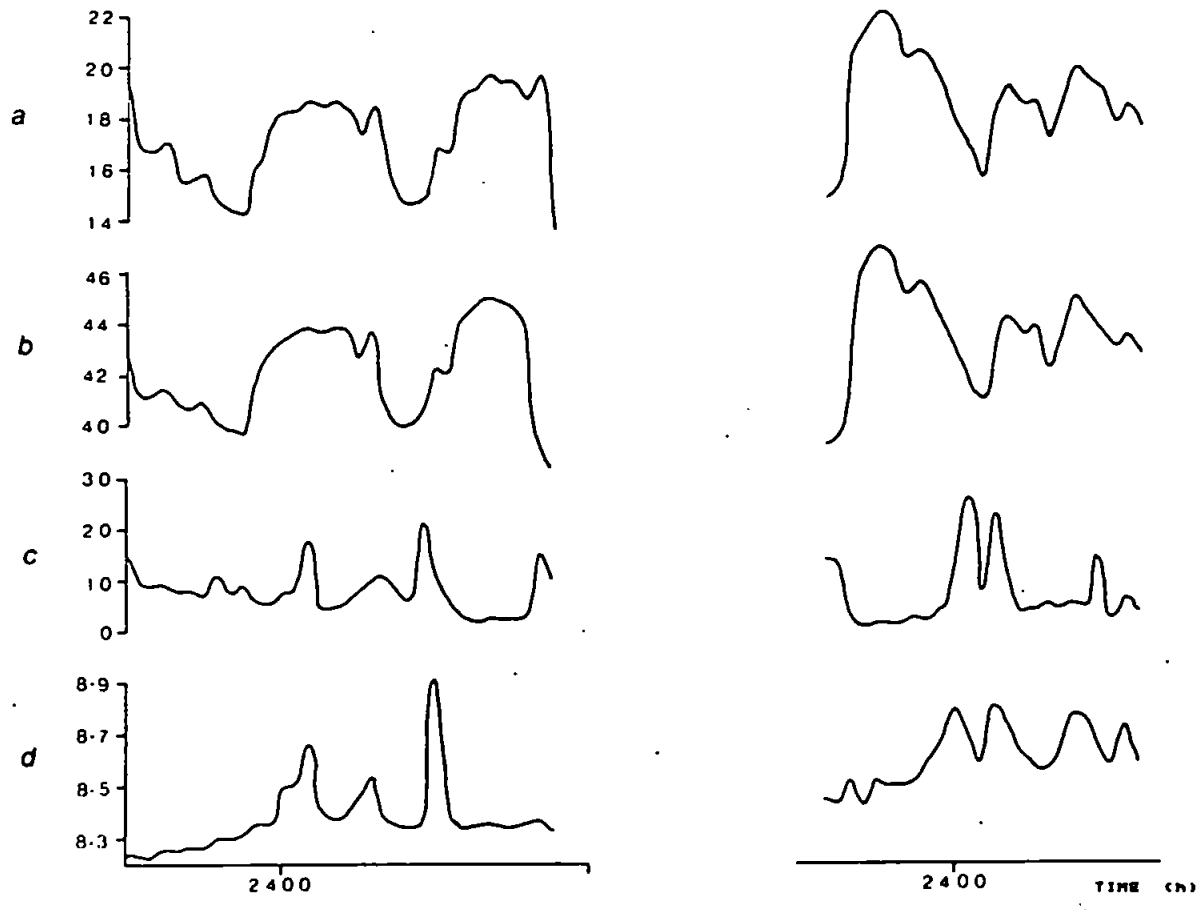


Figure 22. July 1983. Portsmouth to Milford Haven: 1800h 11 July - 2230h 12 July. Milford Haven to Portsmouth: 1900h 17 July to 0700h 18 July. Distribution of (a) temperature (°C), (b) conductivity. (c) Chl F (tus) and (d) pH at 3m.

On the return leg, pH ranged from 8.22 to 8.60, peaking at 2400h, 0130h, 0430h and 0630h 18 July.

On 11-12 July chlorophyll *a* varied from 0.30 to 3.15 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.19-0.56, 0.31-0.80 and 0.00-1.64 mg m^{-3} respectively. On the return leg, chlorophyll *a* varied from 0.30 to 11.51 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.00-0.54, 0.30-2.23 and 0.00-6.01 mg m^{-3} respectively.

4.8. AUGUST 1983

4.8.1. Portsmouth to Milford Haven (31 July-1 August)

Temperature ranged from 15.1 to 19.4°C (Figure 23), with the Ushant front at around 1700h 31 July and the Scilly front at around 2400h 31 July.

Salinity ranged from 31.6 to 33.5‰, varying between 32.5 and 33.5‰ from most of the transect, then dropping to minimum at Milford Haven.

Chl F ranged from 5 to 22 tus, peaking at the temperature gradients.

pH ranged from 8.15 to 8.22.

Chlorophyll *a* varied from 0.57 to 4.1 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.24-0.54, 0.35-1.11 and 0.00-6.14 mg m^{-3} respectively.

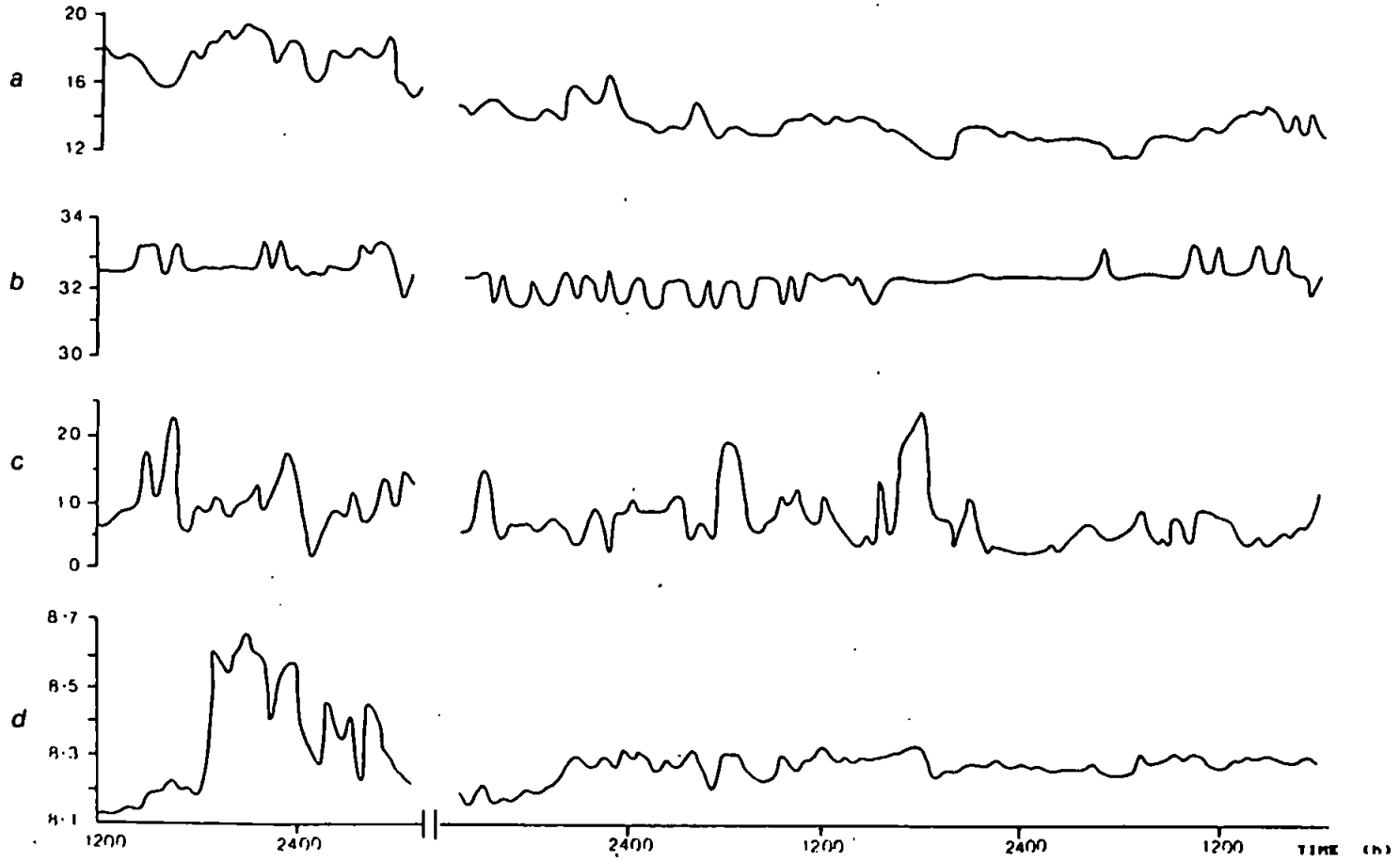


Figure 23. August 1983. Portsmouth to Milford Haven: 1200h 31 July - 0800h 1 August. Milford Haven to Rosyth: 1300h 5 Aug -1900h 7 Aug. Distribution of (a) temperature (°C), (b) salinity (‰), (c) Chl F (tus) and (d) pH at 3m.

4.8.2. Milford Haven to Rosyth (5-7 August)

Temperature ranged from 12.0 to 16.9°C (Figure 23), reaching maximum at 2100h 5 August, and minimum at 1800h (6 August) and 0600h (7 August).

Salinity ranged from 31.2 to 33.1‰, being most variable from 1300h 5 August to around 1200h 6 August.

Chl F ranged from 2 to 23 tus. Chlorophyll *a* varied from 0.25 to 3.90 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.00-2.39, 0.00-1.40 and 0.00-2.00 mg m^{-3} respectively.

4.8.3. Rosyth to Plymouth to Portsmouth (13-16 August)

Figure 24 shows temperature, salinity, Chl F and pH at 3m from Rosyth (1300h 13 August) to Plymouth (0900h 15 August), and from Plymouth (1800h 15 August) to Portsmouth (0800h 16 August).

Temperature ranged from 12.2 to 20.0°C, with the lowest values off the north-east of Scotland.

Salinity ranged from 31.0 to 33.3‰, with one anomalously high reading of 36.0‰ at 0030h on the 16 August.

Chl F ranged from 4 to 32 tus. Chlorophyll *a* varied from 0.18 to 2.96 mg m^{-3}. Chlorphylls *b*, *c*, and phaeophytin *a* ranged from 0.00-0.50, 0.00-1.19 and 0.00-3.6 mg m^{-3} respectively.

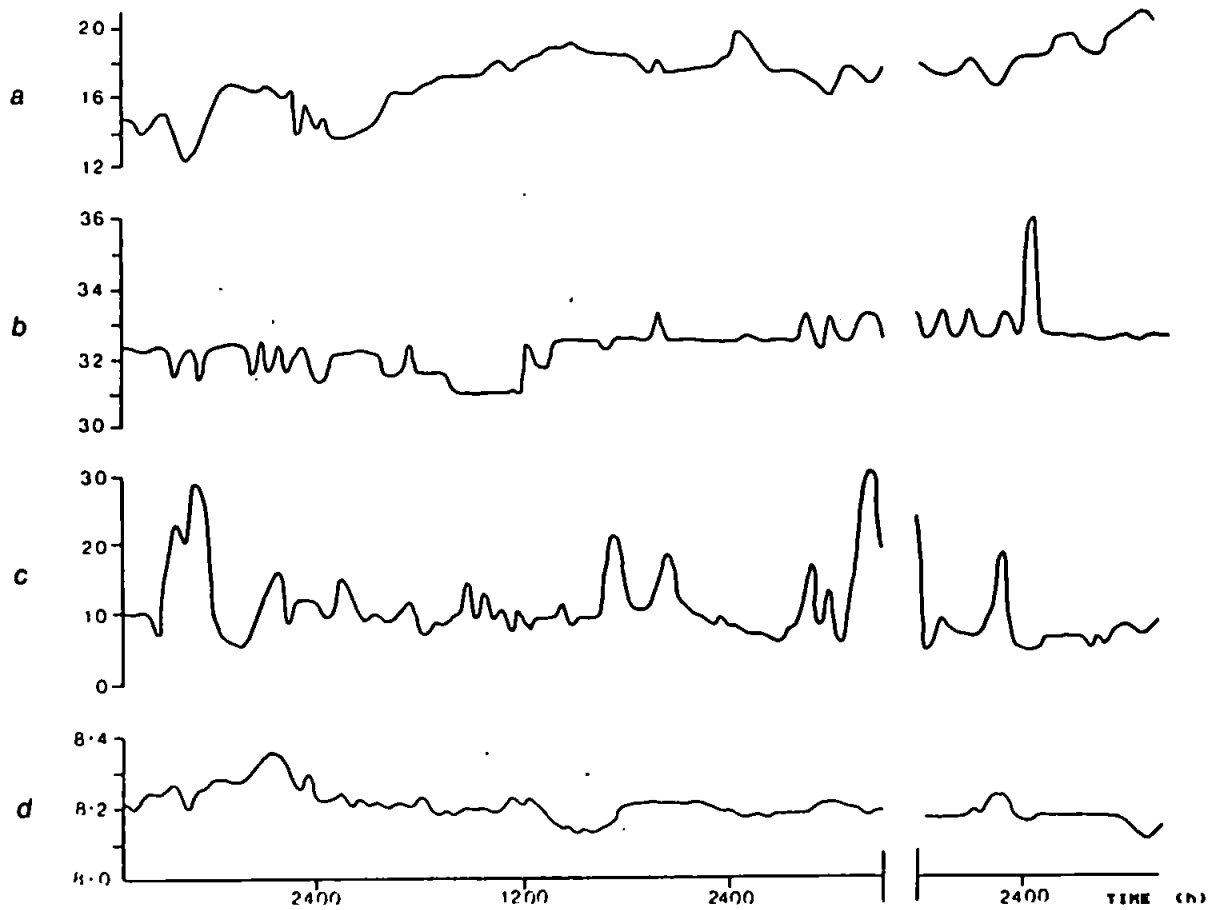


Figure 24. August 1983. Rosyth to Plymouth: 1300h 13 Aug - 0900h 15 Aug. Plymouth to Portsmouth: 1800h 15 Aug - 0800h 16 Aug. Distribution of (a) temperature (°C), (b) salinity (‰), (c) Chl F (tus) and (d) pH at 3m.

4.9. Summary of results.

Tables 1,2 and 3 give a summary of the results of the above surveys:

TABLE 1

Summary of results for Portsmouth to Rosyth transects.

Month	November	April	June
Range in:			
Temperature (°C)	6.0-11.4	7.4-9.8	10.6-16.1
Salinity (‰)	33.0-34.4	30.2-34.5	30.5-33.1
Chl F (tus)	3-13	5-138	6-88
pH	8.58-9.00		8.10-8.50
Chlorophyll *a* (mg m^{-3})	0.20-1.50	0.04-20.82	0.20-10.00
Chlorophyll *b* (mg m^{-3})	0.00-0.30	0.00-2.26	0.00-4.00
Chlorophyll *c* (mg m^{-3})	0.00-0.30	0.00-3.78	0.00-4.00
Phaeophytin *a* (mg m^{-3})	0.00-1.40	0.00-17.28	0.00-22.80

TABLE 2

Summary of results for Portsmouth to Milford Haven transects.

Month	April	7-8 July	11-12 July	17-18 July	August
Range in:					
Temperature (°C)	8.0-9.6	13.6-18.0	13.8-19.81	14.2-21.9	15.1-19.4
Salinity (‰)	32.0-34.4	31.7-34.3	38.4-45.0‰	39.4-47.0‰	31.6-33.5
Chl F (tus)	6-60	2-16	2-21	2-52	5-22
pH		8.27-8.38	8.24-8.92	8.22-8.60	8.15-8.22
Chlorophyll *a* (mg m^{-3})	0.21-3.44	0.31-2.36	0.30-3.15	0.30-11.51	0.57-4.10
Chlorophyll *b* (mg m^{-3})	0.08-1.12	0.20-0.58	0.19-0.56	0.00-0.54	0.24-0.54
Chlorophyll *c* (mg m^{-3})	0.00-0.78	0.22-0.79	0.31-0.80	0.30-2.23	0.35-1.11
Phaeophytin *a* (mg m^{-3})	0.00-1.66	0.00-0.77	0.00-1.64	0.00-6.01	0.00-6.14

(‰ Conductivity)

TABLE 3

Summary of results for Rosyth to Milford Haven transects.

Month	September	December	April	July	August
Range in:					
Temperature (°C)	14,1-18,0	8,0-10,5	7,5-8,4	10,5-14,1	12,0-16,9
Salinity (‰)		32,5-34,5	30,0-33,4	32,0-34,0	31,2-33,1
Chl F (fus)	50-200	0,5-7	6-94	5-30	2-23
pH	7,94-8,12			8,20-8,40	
Chlorophyll *a* (mg m^{-3})		0,00-0,50	0,51-18,21	0,49-2,71	0,25-3,90
Chlorophyll *b* (mg m^{-3})		0,00-1,00	0,10-1,80	0,00-2,43	0,00-2,39
Chlorophyll *c* (mg m^{-3})		0,00-0,40	0,00-3,35	0,00-1,10	0,00-1,40
Phaeophytin *a* (mg m^{-3})		0,00-1,00	0,00-4,36	0,00-4,52	0,00-2,00

4.10. Discussion.

When stratification was at its most pronounced, (June to September), the results of the seasonal surveys indicated that changes in Chl F were consistently associated with temperature and salinity gradients at the shelf sea fronts around the UK. These changes in Chl F were not, however, necessarily co-incident with the temperature and salinity gradients, but often appeared to precede both the temperature and salinity response.

It was expected that during the winter months (November and December), when the water column was well-mixed, Chl F values would be uniformly low, reflecting low phytoplankton productivity, and giving a relatively stable base line around the UK. This was found to be the case,

with Chl F ranging from 0.5-13 tus and chlorophyll *a* from 0.0-1.5 mg m^{-3}.

However, even at these low levels, Chl F showed similar variations to those seen from June to September. These changes in Chl F were, however, associated more with changes in salinity, due to the small temperature differentials during the winter months.

These results indicate that the changes in chlorophyll levels reported in the vicinity of shelf sea fronts (eg. Savidge, 1976) during the summer months are likely to be consistent, not transient, features, which are also associated with temperature and salinity gradients at other times of the year.

SECTION 5

5. AN INVESTIGATION INTO CHANGES IN PHYSIO-CHEMICAL PARAMETERS ACROSS A SHELF SEA FRONT (USHANT 1984).

5.1. Introduction.

5.2. Surface measurements.

5.2.1. Introduction .

5.2.2. Rates of change in surface parameters.

5.2.3. Determination of alarm/false alarm rates.

5.3. Vertical structure of the water column across the front.

5.3.1. Introduction

5.3.2. North/south transects.

5.3.3. East/west transects.

5.4. Movement of the front.

5.5. Discussion.

5. AN INVESTIGATION INTO CHANGES IN PHYSIO-CHEMICAL PARAMETERS ACROSS A SHELF SEA FRONT (USHANT 1984).

5.1. INTRODUCTION

The previous surveys in this study demonstrated that changes in Chl F occur in the vicinity of both a deep-sea (Section 3) and a shelf sea front (Section 4). Both studies also indicated that a distance advantage may be gained by using surface measurements of Chl F, rather than temperature, in the detection of the front. The seasonal studies also indicated that pH changes may also be associated with frontal regions.

A further study was therefore undertaken in June 1984 in order to investigate the changes in temperature, Chl F, and pH at 3m across the Ushant front, and to determine if the rates of change in these parameters on approaching a front could be used as a detection method.

Fluctuations in the *in vivo* fluorescence of chlorophyll *a* have been shown to vary with environmental conditions and species composition (Blasco, 1973). These fluctuations are reported to be eliminated when photosynthetic electron transport is blocked by DCMU [3-(3,4 dichlorophenyl)-1, 1-dimethyl urea] addition. Slovacek & Hannan (1977) therefore suggested that DCMU-enhanced fluorescence emission could be used to give a more accurate

determination of chlorophyll *a* concentrations. The effects of DCMU addition on discrete samples were therefore investigated in order to determine whether this would enhance the potential of Chl F as a detection method.

Chlorophyll measurements represent only one aspect of the biomass. Discrete samples were therefore taken to investigate changes in ATP in the water column across the front, and to determine if ATP biomass estimations also showed potential as an advance warning technique.

5.2. SURFACE MEASUREMENTS

5.2.1. Introduction

A series of crossings of the front was made on the 13 and 14 June 1984 (Figure 25).

These ranged from short crossings of less than 5 miles, where the front was crossed almost at right angles, to longer crossings where the ship steamed along the front for more than 40 miles, crossing at a very shallow angle. Between these two extremes were areas where the ship apparently started to cross the front, but then moved back into the original water mass. These areas where the ship approached the front, but did not cross it, are refered to in the text as "skirtings".

Since the results obtained for both 13 June and 14 June were very similar, only those for 13 June will be presented in detail.

On the 13 June, SST (Figures 26 & 27) showed that the front was crossed 8 times (0700 to 0800h, 0900 to 1000, 1050 to 1130, 1350 to 1430, 1600 to 1630, 1700 to 1830, 1900 to 2100 and at 2130 to 2230h), and skirted on 10 occasions.

SST changed by >2°C across the front, being <12.5°C in the mixed water, and reaching a maximum of 15.5°C in the stratified water. These temperature changes were associated with changes in both Chl F and pH (Figures 26-27), with Chl F ranging from as low as 20 tus in the mixed

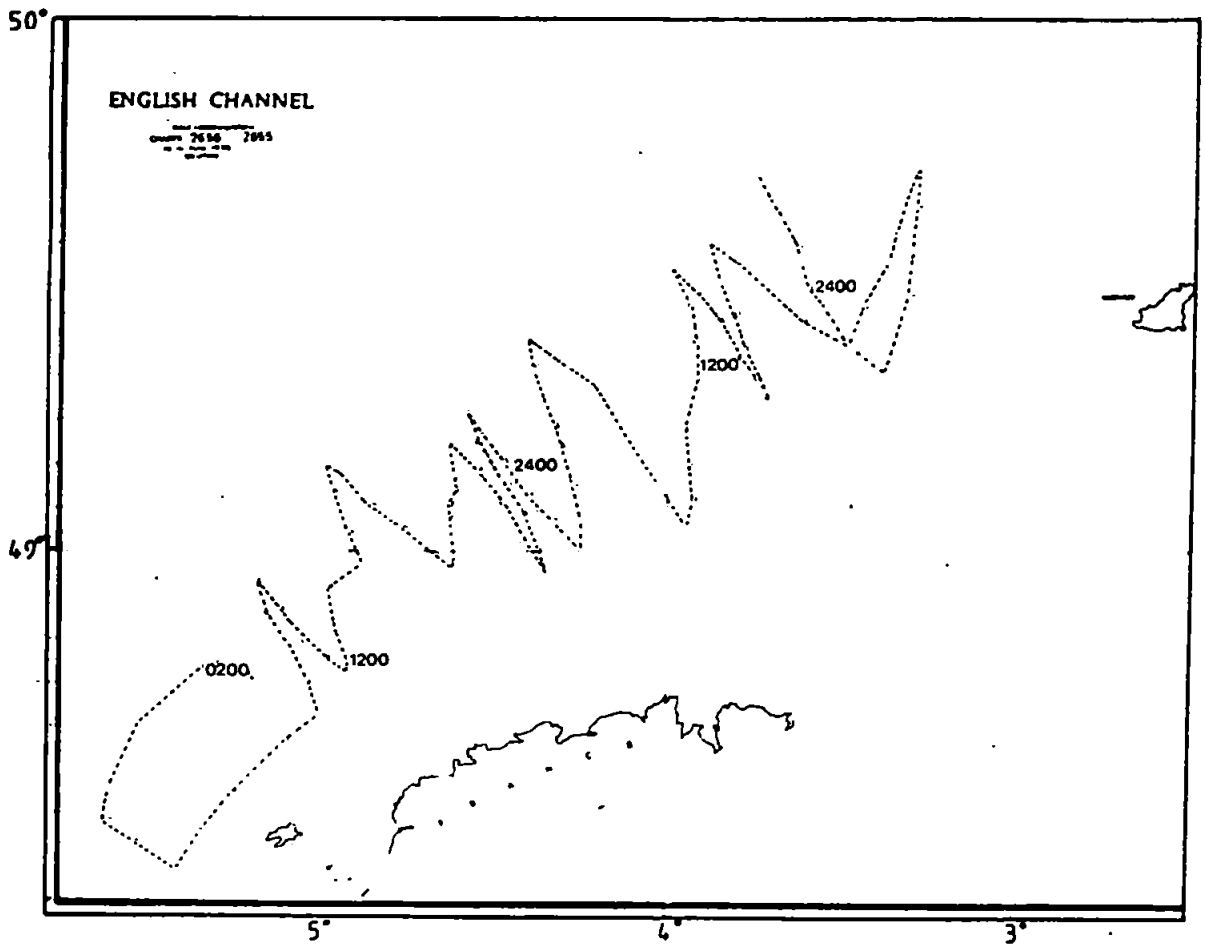


Figure 25. Ships track, 13 & 14 June 1984. All times GMT.

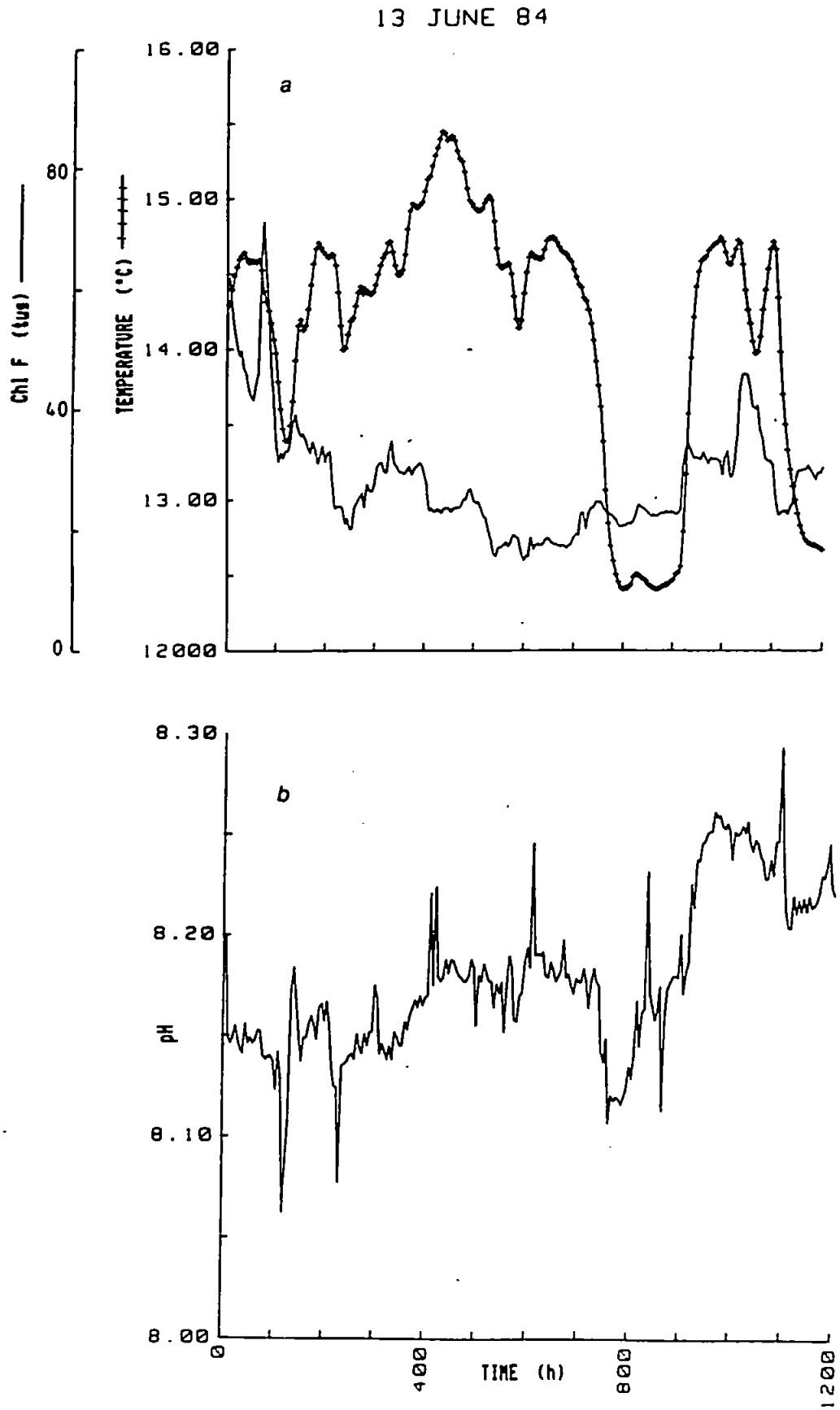


Figure 26. (a) Temperature (°C), Chl F (tus) and (b) pH distribution across the Ushant front, 13 June 1984.

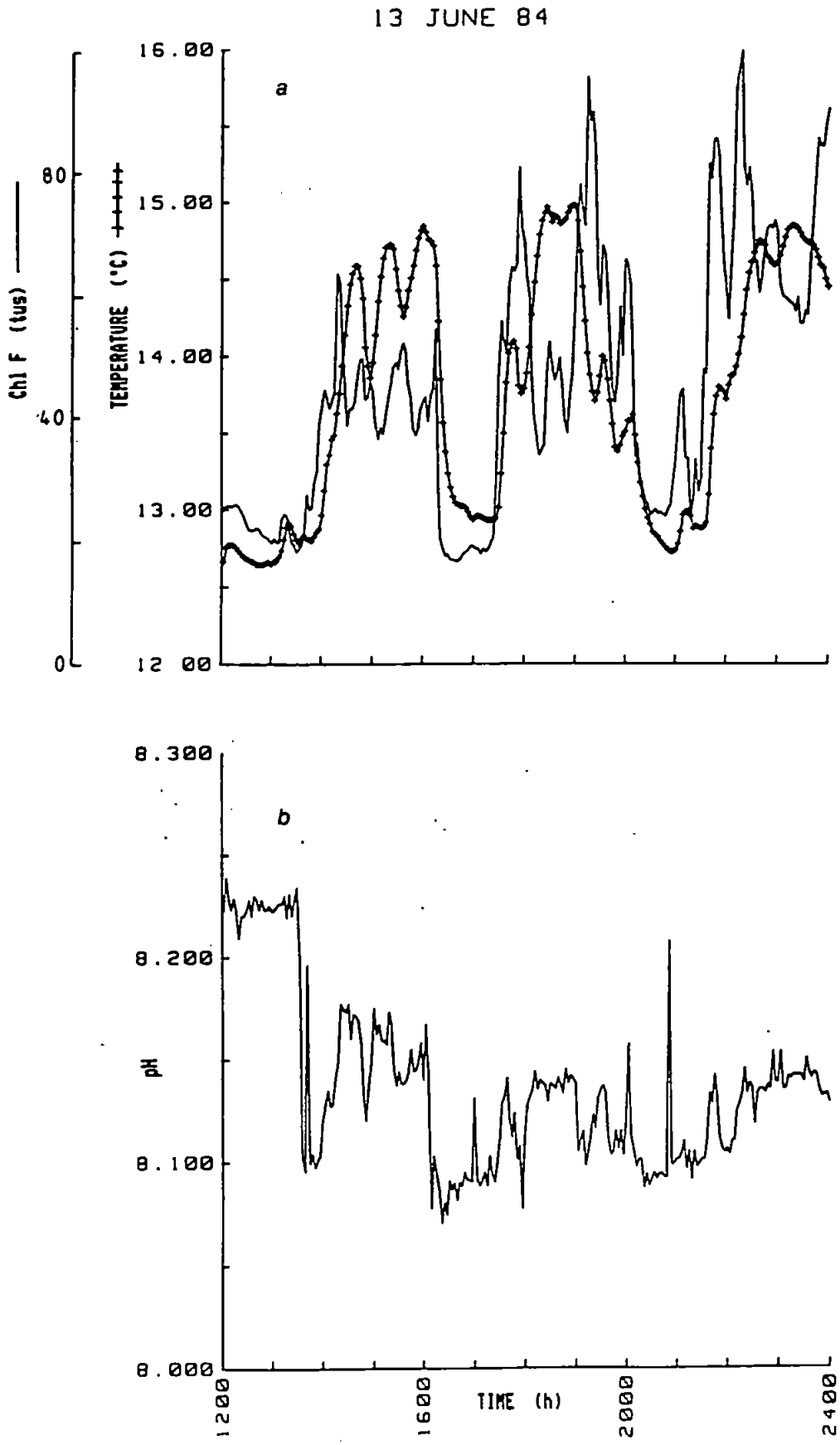


Figure 27. (a) Temperature (°C), Chl F (tus)and (b) pH distribution across the Ushant front, 1200-2400h 13 June 1984.

water to 100 tus in the stratified water. pH ranged from 8.05 to 8.30 pH units, and although the signal was very noisy, values were generally higher in the stratified water.

The surface monitoring data were subsequently recorded on a BBC microcomputer, and the rates of change in each parameter calculated. Both alarm, and false alarm, rates on approaching the front were then determined for each parameter, and the results compared.

5.2.2. Rates of change in surface parameters.

Rates of change between data points (which were 0.5 miles apart) were computed as a percentage of the previous reading.

A "best-fit" scenario was determined, whereby the highest percentage rate of change was calculated, for each parameter, at which the maximum number of crossings of the front were detected, regardless of the number of false alarms. These rates are represented as T1, C1 and pH1 in Figures 28 - 31, and were found to be 0.5%, 10.0% and 0.4% respectively. The sensitivity was then increased to a point just below that at which alarms were flagged continuously. These levels were 0.1% (T2), 5.0% (C2) and 0.3% (pH2). Alarms were then flagged for both sets of readings.

5.2.3. Determination of alarm/false alarm rates.

The T2 (0.1%) readings were almost continuous, making the separation of alarms difficult. Therefore, where two or more consecutive alarms were flagged, the alarms are represented as a block, and the block taken as a single alarm. Alarms were declared false if the flags raised were not in proximity to an area of temperature change.

Results for the 13th June are summarised in Table 4. However, the complexity of the data is not evident from the table, and can best be illustrated by the use of specific examples from 13 and 14 June. The remainder of the results for 13 June are given in Appendix 2.

TABLE 4

Summary of results obtained on 13 June 1984.

No. of Crossings 8 No. of Skirtings 10

	No. Crossings Detected	No. Skirtings Detected	No. False Alarms	No. Detections in Advance of T1
T1	8	9	0	
T2	8	10	12	15
C1	8	10	0	14
C2	8	10	3	16
pH1	5	3	4	3
pH2	6	4	5	4

Where rates of change are T1 (0.5%), T2 (0.1%); C1 (10.0%), C2 (5.0%); pH1 (0.4%), pH2 (0.3%).

Example 1.

Where C1 and pH1 flag alarms in advance of T1.

For the period 0700 to 0900h, the number of alarms flagged at each rate of change for each parameter are represented diagrammatically in Figure 28, and the results summarised below in Table 5.

TABLE 5

13 June 1984, 0700 - 0900h

	Front Detected?	Advantage over T1 (miles)	False Alarms
T1	Yes		0
T2	Yes	5,0	4
C1	Yes	3,5	0
C2	Yes	5,0	1
pH1	Yes	0,5	2
pH2	Yes	0,5	3

Where rates of change are T1 (0,5%), T2 (0,1%); C1 (10,0%), C2 (5,0%); pH1 (0,4%), pH2 (0,3%).

In this example T2, C1, C2, pH1 and pH2 all flagged alarms in advance of T1. The highest rate of false alarms was given by T2, and the lowest by C1 and C2.

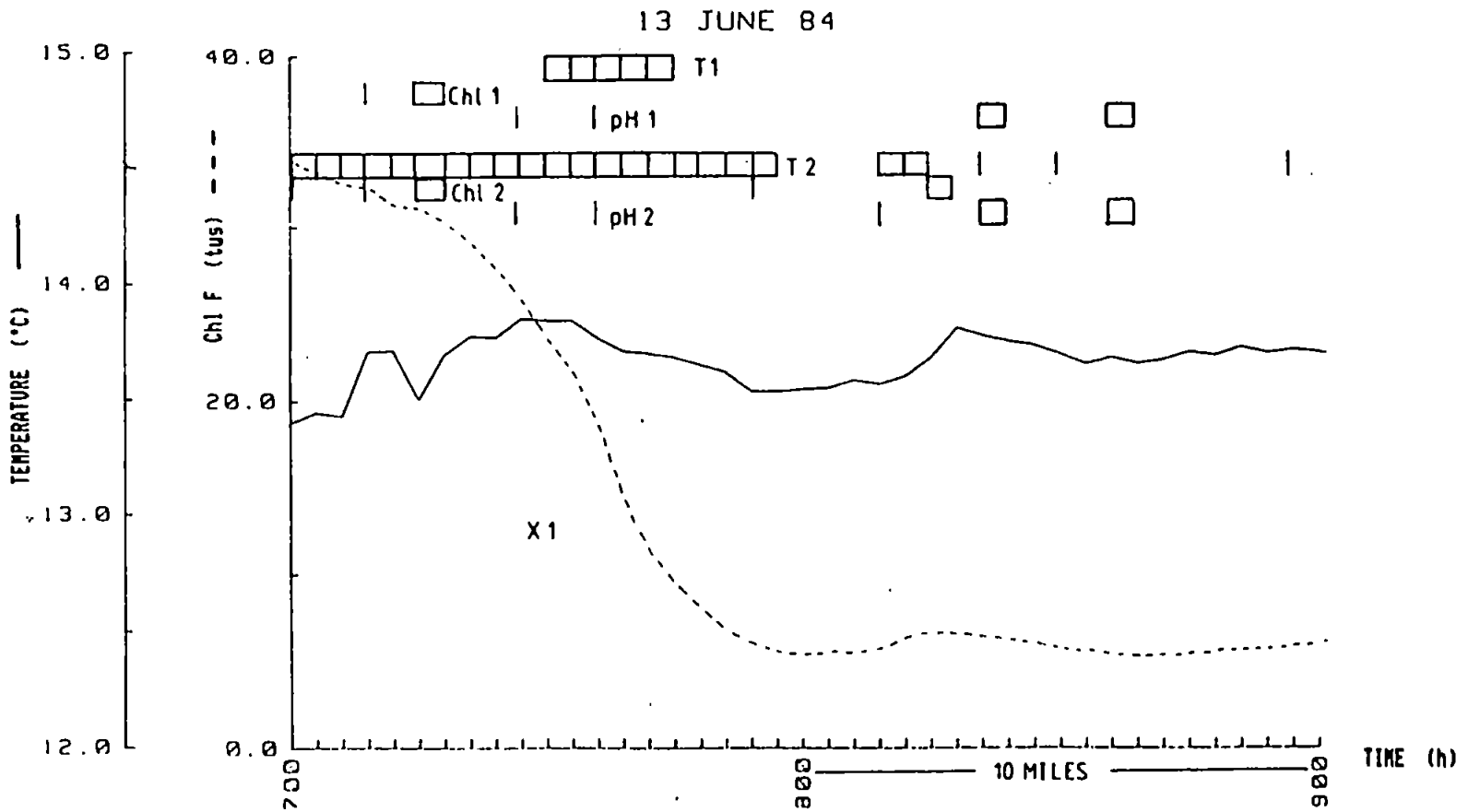


Figure 28. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) at crossing X1 of the Ushant front, 13 June 1984. C1 & pH1 alarms flagged in advance of T1.

The designation of an alarm as false can be difficult, as can be seen from Figure 28, where the majority of "false" alarms are associated with the slight temperature increase at 0815h.

Example 2.

Where C1 and pH1 show no advantage over T1.
Table 6 summarises the results for the period 0830 to 1000h (Figure 29).

TABLE 6

13 June 1984, 0830 - 1000h

	Front Detected?	Advantage over T1 (miles)	False Alarms
T1	Yes		0
T2	Yes	1.5	3
C1	Yes	0.0	0
C2	Yes	0.0	1
pH1	Yes	0.0	0
pH2	Yes	1.5	0

Where rates of change are T1 (0.5%), T2 (0.1%); C1 (10.0%), C2 (5.0%); pH1 (0.4%), pH2 (0.3%).

This crossing is an example where C1 shows no advantage over temperature in detecting the front. The designation of a flag as a false alarm again poses problems: the T2 alarms are flagged almost continuously throughout the

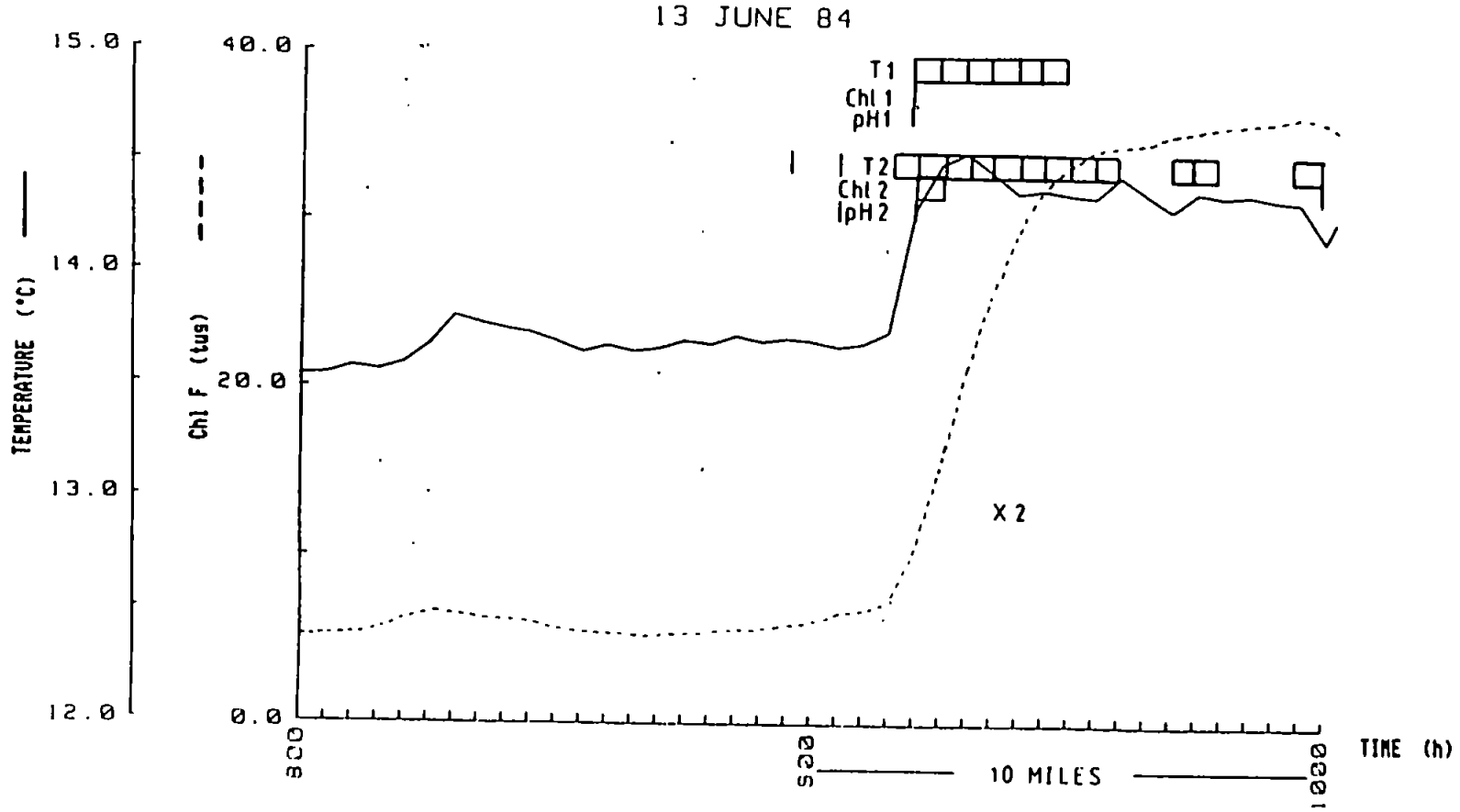


Figure 29. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) at crossing X2 of the Ushant front, 13 June 1984. T1, C1 and pH1 alarms flagged simultaneously.

period; and the T2 and C2 alarms at around 1000h, which have been designated as "false" in the above table, might reasonably be taken as warnings of the skirting of the front which occured at 1006h, and would therefore not be "true" false alarms.

Example 3.

Detection of skirtings of the front.

The period 1000 to 1200h, 13 June, covered two skirtings and one crossing of the front (S1, S2 & X3, Figure 30). The results are summarised in Table 7.

The first skirting of the front (S1) was not detected by either T1, pH1 or pH2. It was, however, clearly indicated by both C1 and C2. Since the T2 alarms are again flagged almost continuously, the advantage gained by using T2 over T1 cannot be considered accurate.

S2 was detected by both rates of change for temperature and Chl F, but not by pH.

X3 was detected, at both rates of change, by all three parameters.

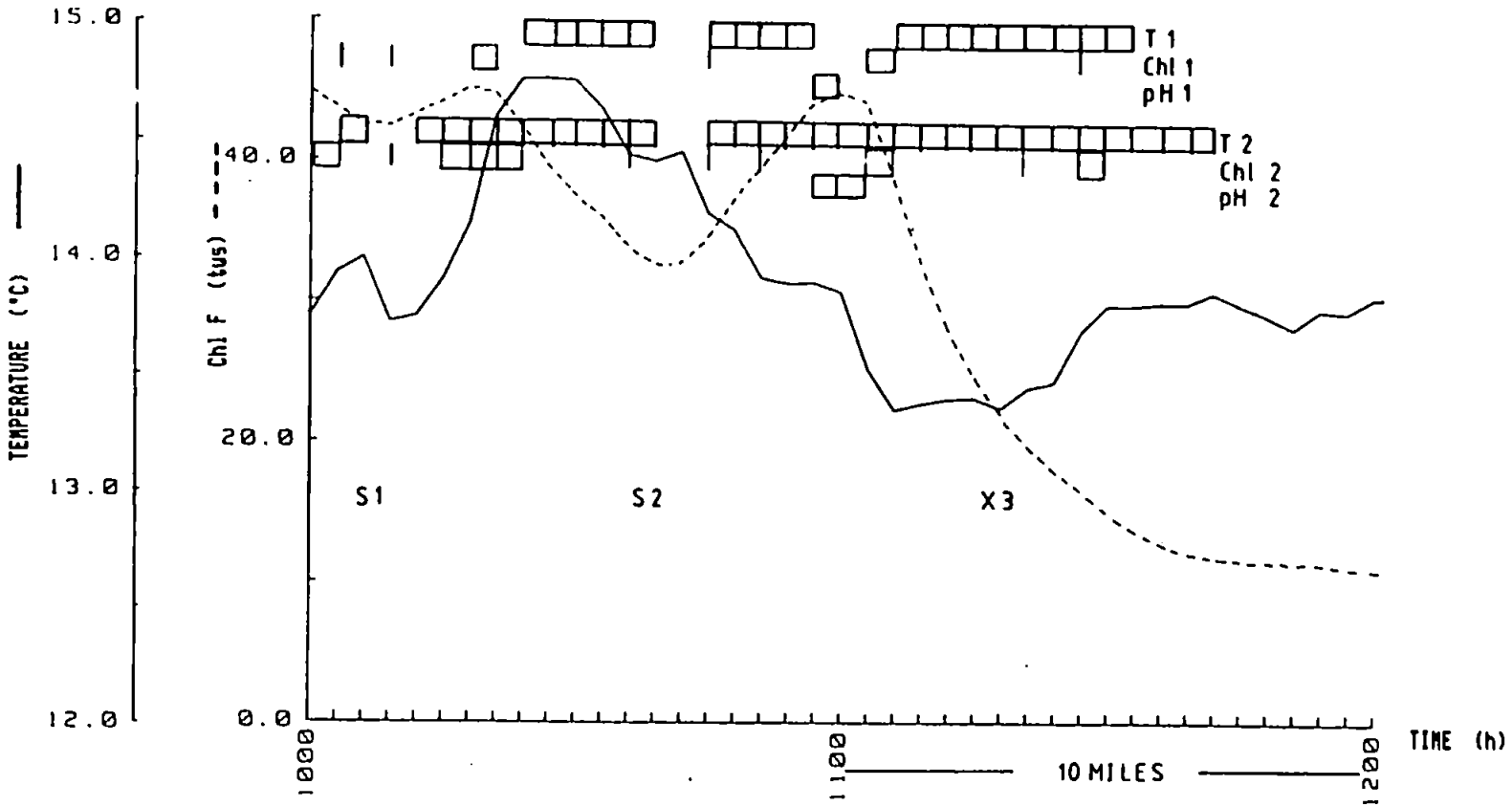


Figure 30. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) at skirtings S1, S2, and crossing X3 of the Ushant front, 13 June 1984. S1 detected by C1, but not by T1 & pH1.

TABLE 7

13 June 1984, 1000 - 1200h.

	T1	T2	C1	C2	pH1	pH2
S1 detected?	No	Yes	Yes	Yes	No	No
Advantage over T1 (miles)		1,0	3,5	4,0	0,0	0,0
S2 detected?	Yes	Yes	Yes	Yes	No	No
Advantage over T1 (miles)		2,0	1,0	1,5	0,0	0,0
X3 detected?	Yes	Yes	Yes	Yes	Yes	Yes
Advantage over T1 (miles)		3,5	0,5	0,5	1,5	1,5
False alarms	0	0	0	0	0	0

Where rates of change are T1 (0,5%), T2 (0,1%); C1 (10,0%), C2 (5,0%); pH1 (0,4%), pH2 (0,3%).

Example 4

Traversing the front at a shallow angle.

During the period 0400 to 0900h 14 June, a single transit of the front was made which covered a distance of over 40 miles (Figure 31). Alarms at both levels of sensitivity were flagged throughout the duration of the crossing by both temperature and Chl F, with pH raising flags only at the beginning and middle of the transit.

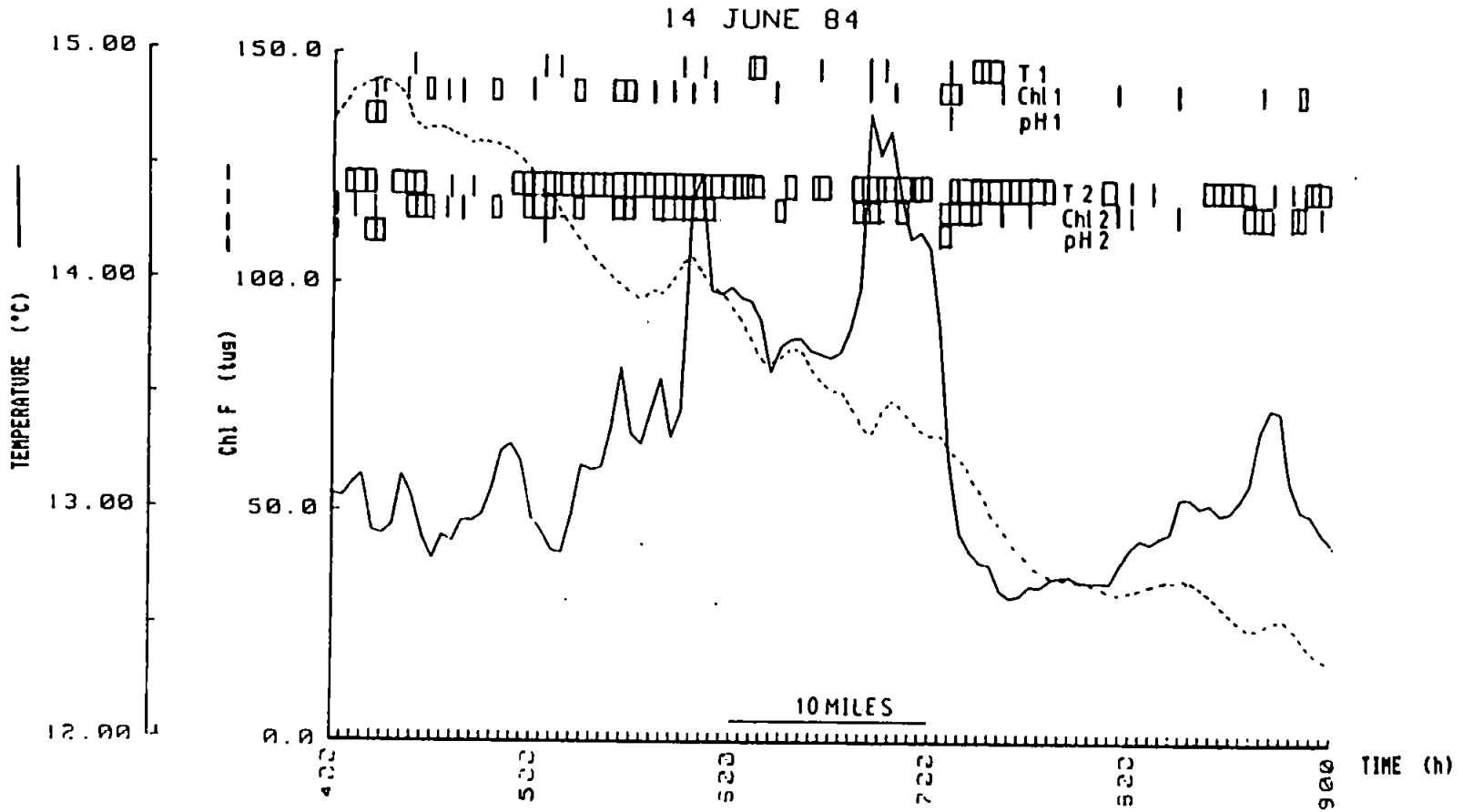


Figure 31. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) where the Ushant front was crossed at a shallow angle, 14 June 1984.

5.3. VERTICAL STRUCTURE OF THE WATER COLUMN ACROSS THE FRONT.

5.3.1. Introduction

It has been shown that the monitoring of Chl F can be used to detect the surface position of frontal systems, often in advance of temperature. A study of a portion of the Ushant front was therefore undertaken in order to investigate whether

(a) chlorophyll levels could also be used to detect subsurface fronts

(b) ATP biomass estimations showed potential as a detection technique

(c) the effects of DCMU addition on phytoplankton fluorescence could enhance the efficiency of using Chl F as a detection method.

The surface position of the front for the period 22 to 27 June 1984 was fixed by continuous monitoring of temperature and Chl F at 3m (see Appendix 2).

A series of depth profiles across the front along North/South and East/West transects was planned in order to investigate the vertical and horizontal distribution of temperature and Chl F. ATP biomass estimations and DCMU addition were also carried out on discrete samples taken on the north/south transects.

This trial was carried out in association with ARE (Holton Heath). The *in vivo* fluorescence profiles of

chlorophyll *a* were measured continuously using the ARE Holton Heath multisensor profile system, and converted to mg m^{-3} of chlorophyll *a* (Chl F').

Positions of the profile stations are shown in Figures 32 & 39, with those marked 'H' comprising part of the study being carried out by ARE.

5.3.2. North/South Transects.

(a) Distribution of temperature and Chl F' across the front.

1st Transect (Stations 16 - 21).

SST fell steadily from north to south, with temperatures at 0 to 80m ranging from 14.1-12.1°C at station 16, and from 12.8-12.0°C at station 21.

The thermocline also weakened steadily from north to south (Figure 33). Stations 16, 17 and 18 were strongly stratified, but at station 19 the thermocline (14-18m) became weaker (12.0-13.3°C). At station 20 the thermocline weakened further (14-20m, 12.0-13.2°C), and by station 21 the water column was almost isothermal.

The surface monitoring data (Appendix 2) also placed stations 19 & 20 on the front.

Chl F' (Figure 33), Chl S and ATP (Appendix 2) were all more evenly distributed throughout the water column in the mixed water mass at station 21, but no major

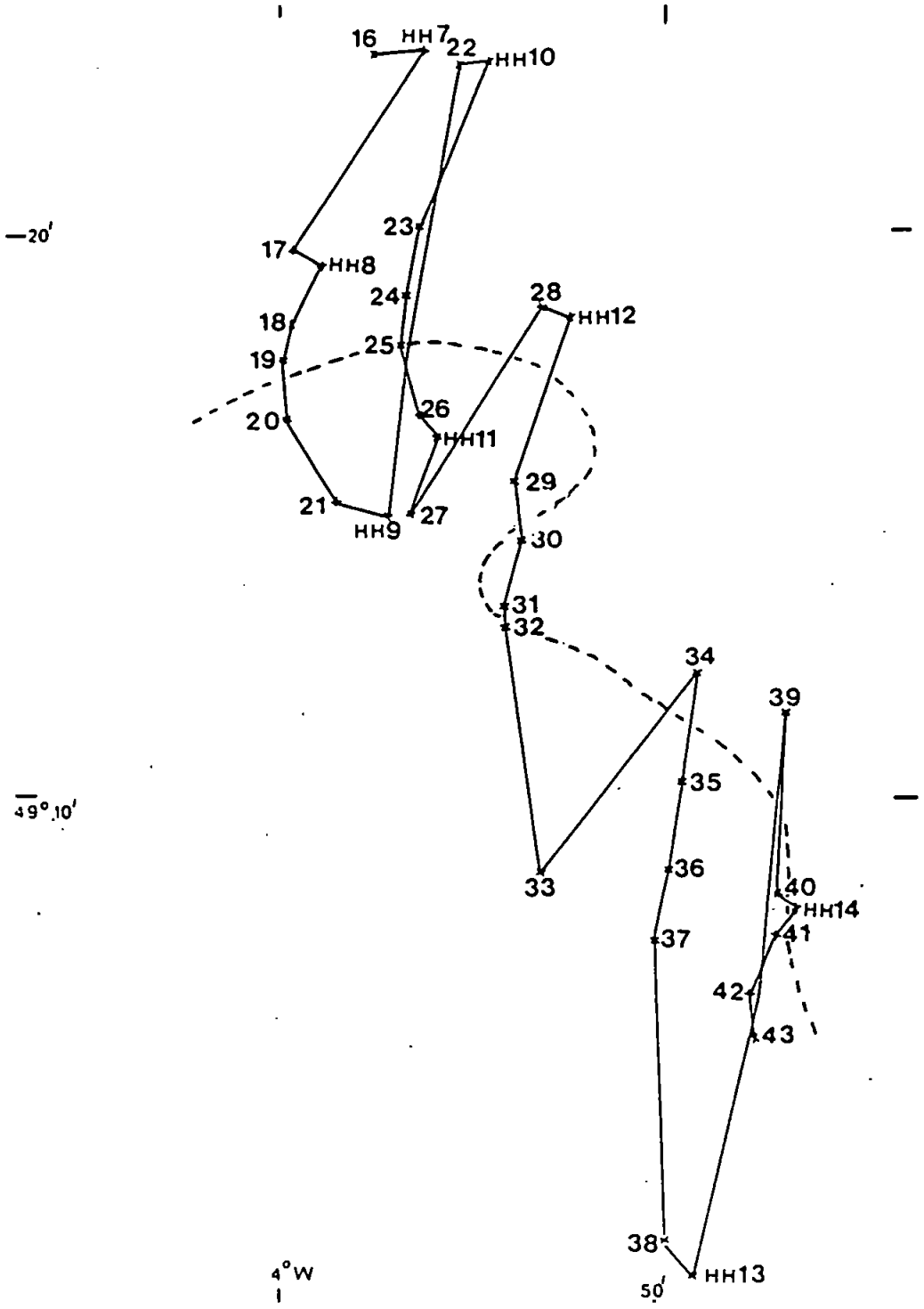


Figure 32(a). North/south transects across the Ushant front, 22-24 June 1984. Ships track and profile stations 16 to 43.

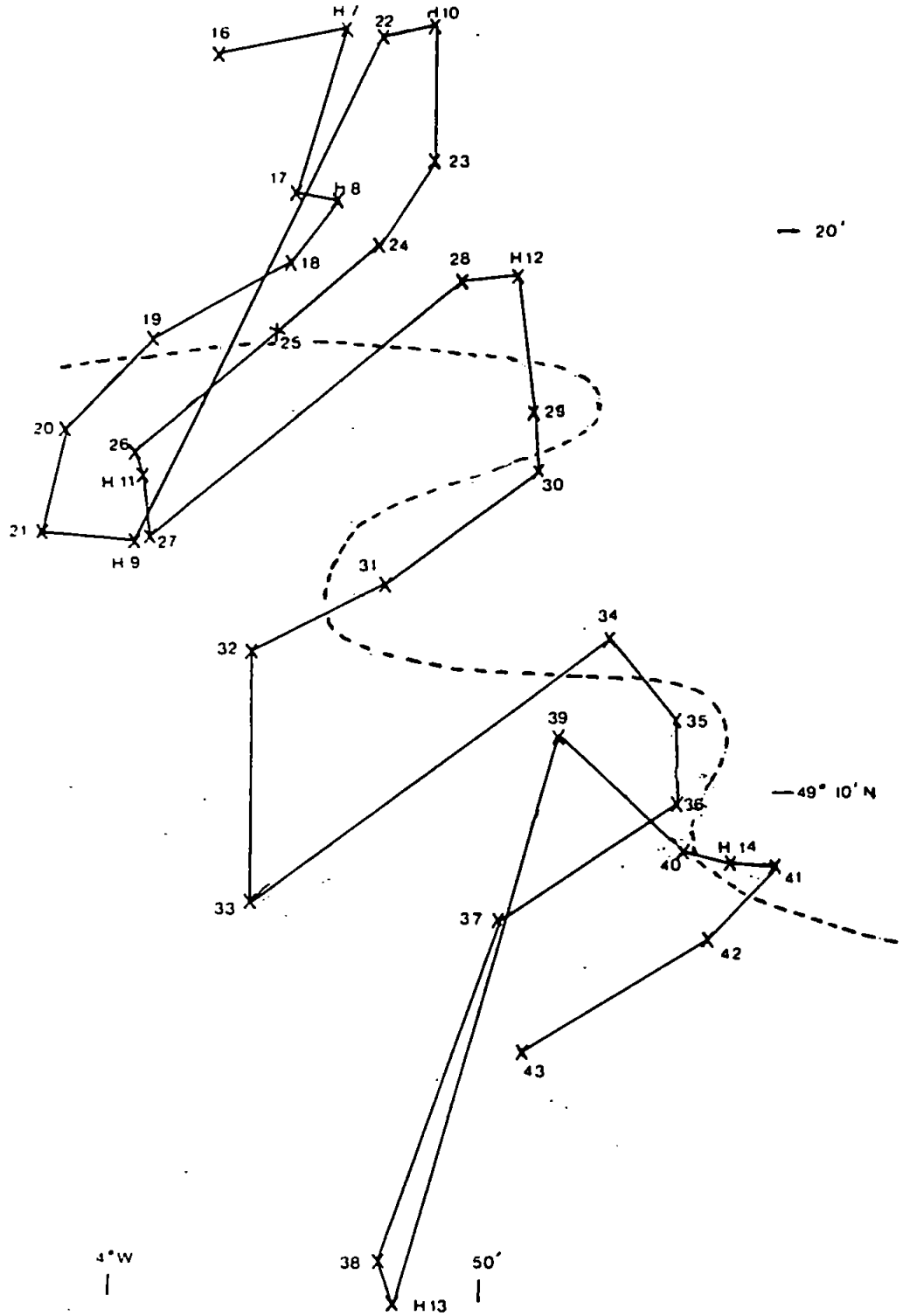


Figure 32(b). Tidally corrected profile stations 22-24 June 1984.

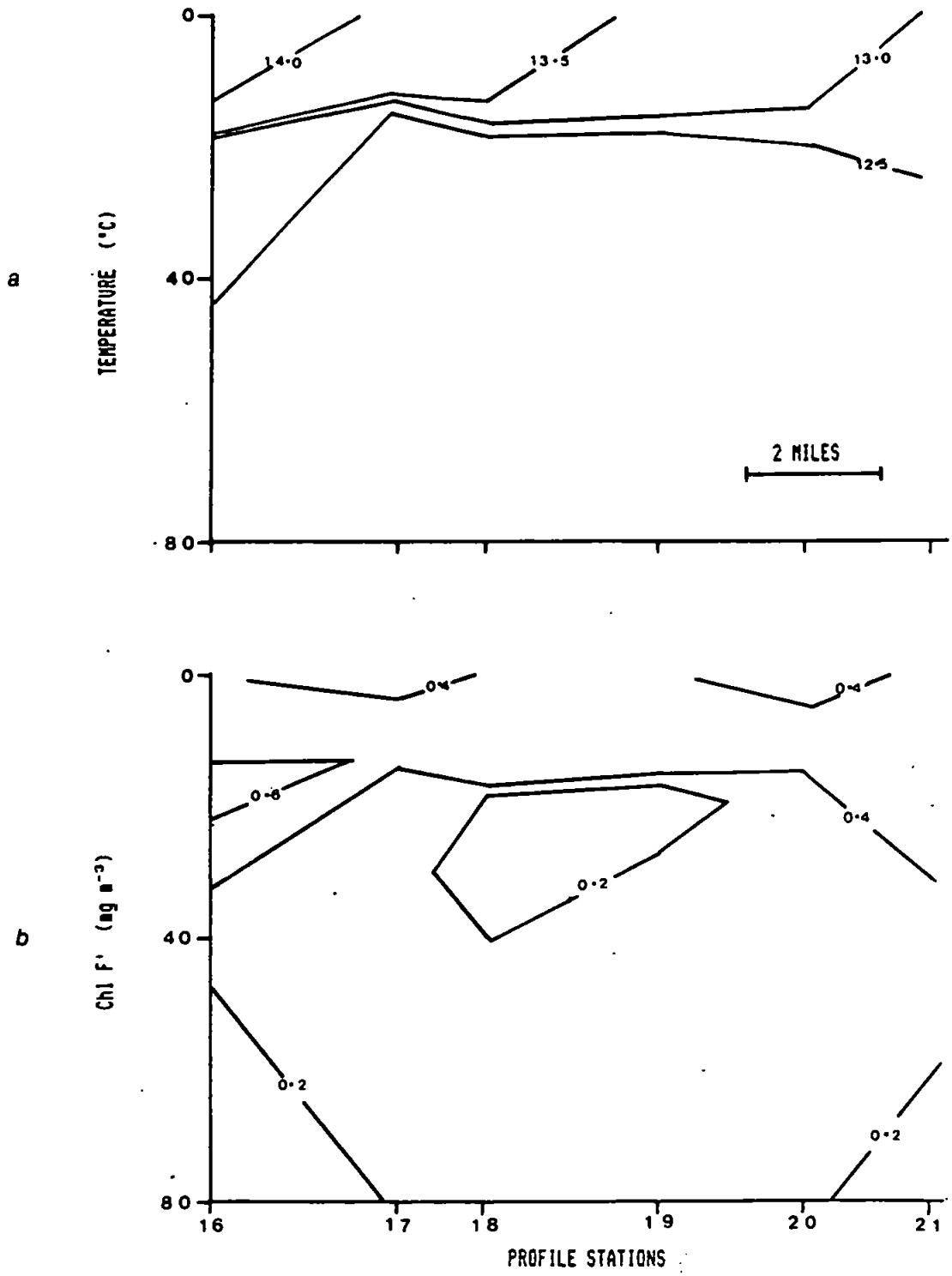


Figure 33. Ushant front, 22 June 1984. Transect 1, profile stations 16-21. Distribution of (a) temperature (°C) and, (b) Chl F' (mg m^{-3}) with depth.

difference in the distribution of pH with depth was evident.

2nd Transect (Stations 22 - 27)

SST again increased towards the south of the transect, with temperatures at 0 to 80m ranging from 13.8-11.9°C at station 22, and from 12.8-12.0°C at station 27. The surface monitoring programme indicated that stations 22-25 were in stratified water, 26 at the front and station 27 in mixed water. The depth profile data (Figure 34) however, indicated that stations 22-24 were in stratified water, 25 and 26 were frontal, with station 27 being in mixed water.

Chl F' data (Figure 34) show an increase in chlorophyll above 20m at stations 25-27, in the well-mixed and frontal areas.

3rd Transect (Stations 28 - 33)

The continuous surface monitoring indicates that station 28 was in stratified water, 29 in mixed, and 30-33 in stratified.

At station 28, the temperature over the water column ranged from 13.7-12.0°C, with a strong thermocline (13.5-12.0°C) at 16-23m (Figure 35). At station 29, in the mixed water mass, the temperature range was 12.9-12.0°C, with a much weaker thermocline (12.8-12.0°C) at 21-25m. Station 30 showed a rise in surface temperature (13.3°C), and appeared to be frontal, with a strong thermocline

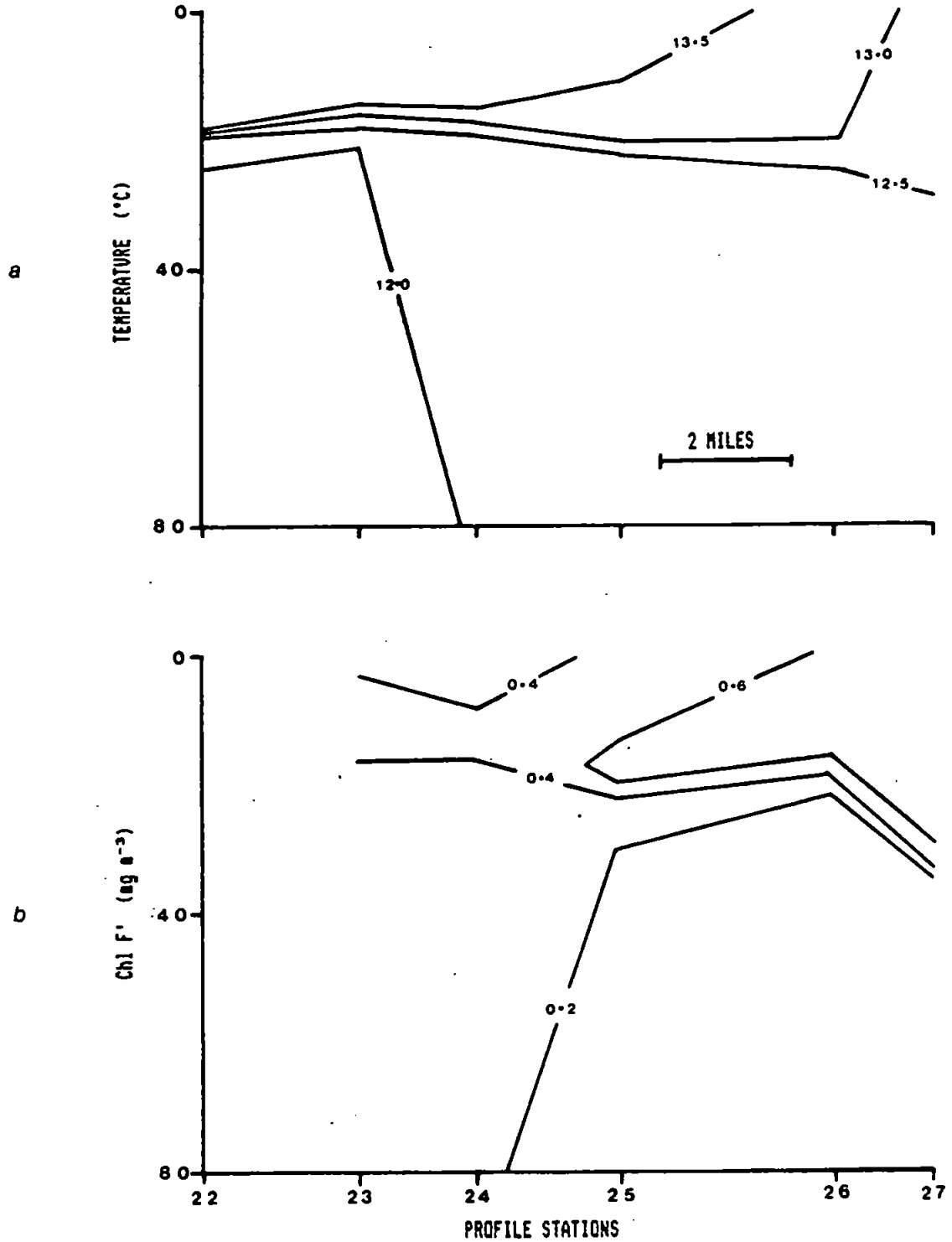


Figure 34. Ushant front, 22 June 1984. Transect 2, profile stations 22-27. Distribution of (a) temperature (°C) and, (b) Chl F' (mg m^{-3}) with depth.

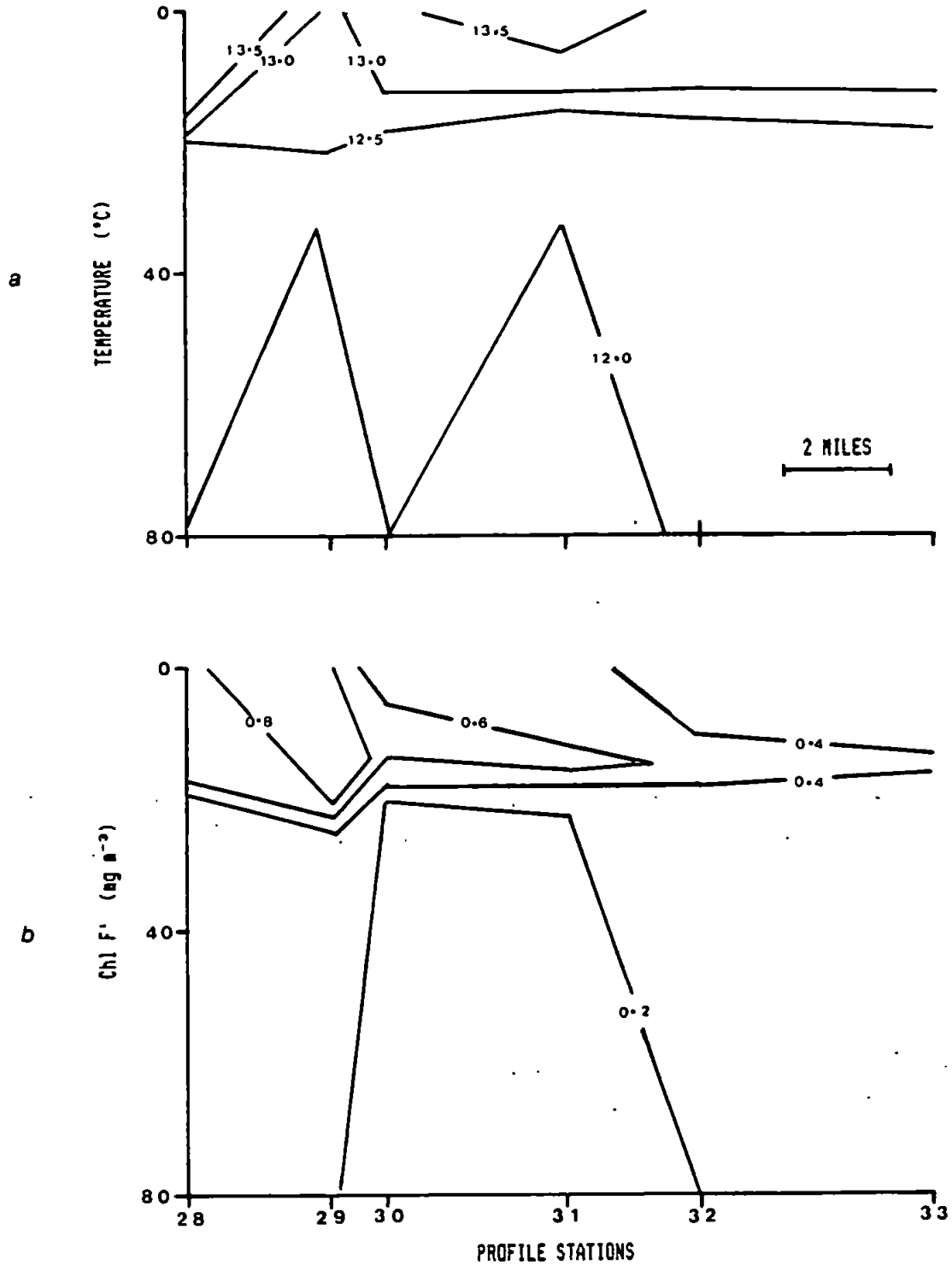


Figure 35. Ushant front, 23 June 1984. Transect 3, profile stations 28-33. Distribution of (a) temperature (°C) and, (b) Chl F' (mg m^{-3}) with depth.

(13.3-12.0°C) at 12-20m. Station 31 was frontal, tending towards stratified, and stations 32 and 33 mixed. At station 33, however, the 80m temperature rose to 12.2°C, thereby reducing the temperature differential over the water column.

Chl F' values (Figure 35) were <0.4 mg m^{-3} beneath the 12°C isotherm throughout. Values were highest (0.21-0.92 mg m^{-3}) at station 29 in the mixed water, but were also high above 20m at stations 28 (0.21 - 0.75 mg m^{-3}) & 30 (0.18-0.71 mg m^{-3}), falling to 0.19 - 0.35 mg m^{-3} at station 31, then increasing slightly to 0.2 - 0.66 mg m^{-3} at station 32 (peaking to maximum at the thermocline). At station 33 the range in Chl F' was 0.2 - 0.45 mg m^{-3}.

4th Transect (Stations 34 - 38)

Continuous surface monitoring placed stations 34 & 35 in stratified water and stations 36-38 on the front. The vertical profile data (Figure 36), however, shows that although SST at stations 36-38 (13.5°C) was comparable with the frontal stations on the previous surveys, station 36 was frontal, and stations 37 & 38 well-mixed. The 80m temperature increased from 12.2°C at station 34, to 15.5°C at station 38.

Chl F values (Figure 36) were higher along this transect than in the more northerly transects. At station 34, Chl F' ranged from 0.23 - 0.92 mg m^{-3}, peaking at the base of the thermocline (20m), dropping to their lowest values (0.22 - 0.48 mg m^{-3}) at station 35, although

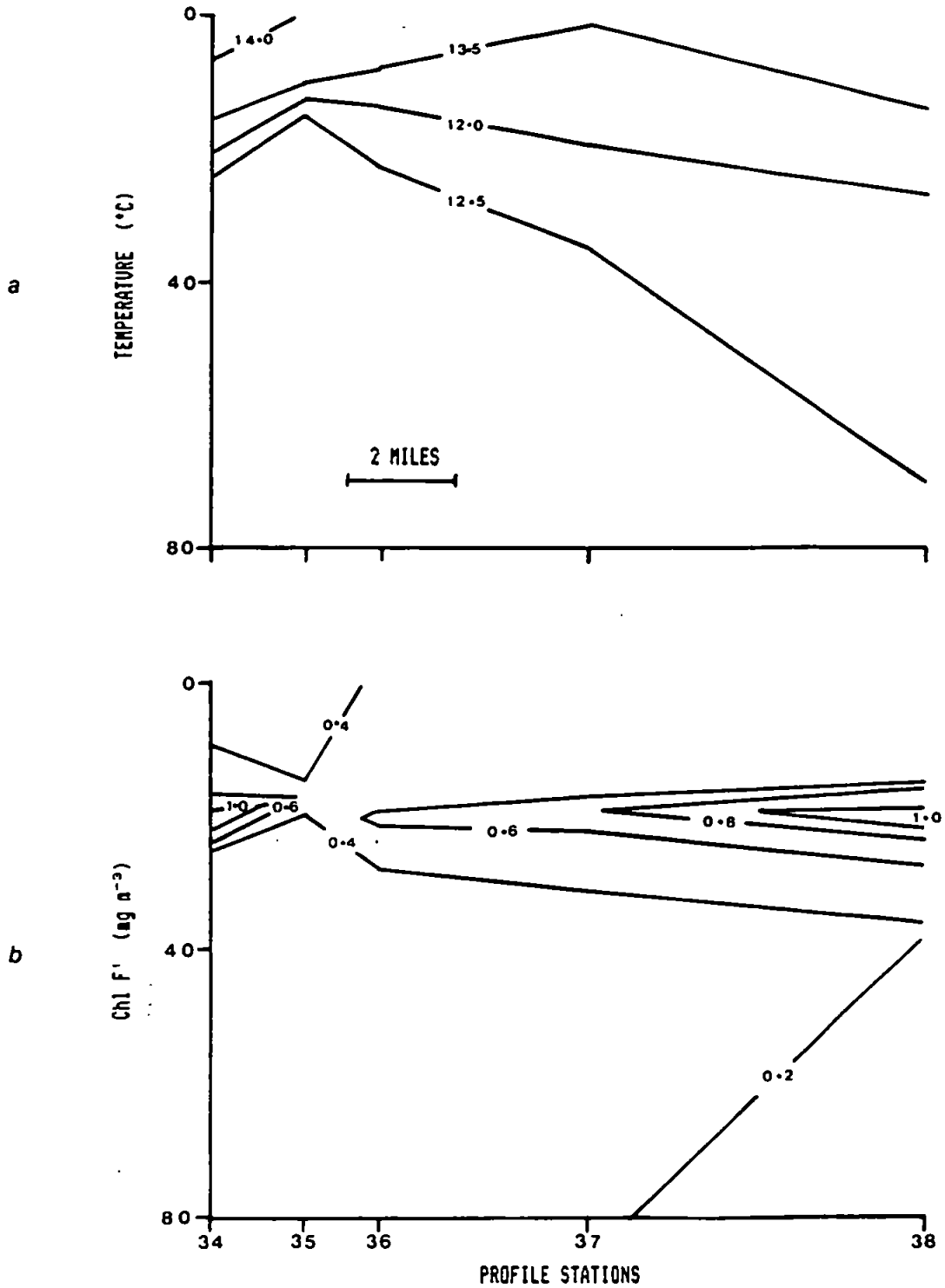


Figure 36. Ushant front, 23 June 1984. Transect 4, profile stations 34-38. Distribution of (a) temperature (°C) and, (b) Chl F' (mg m^{-3}) with depth.

still peaking at the base of the thermocline (15m). At station 38, there was a marked increase in Chl F', with values ranging from 0.18 - 1.44 mg m^{-3}. The highest values along this transect were in the upper 30m of the mixed water mass from station 36 to station 38, being concentrated at 15-25m (at around the depth of the thermocline in the stratified water).

5th Transect (Stations 39 - 43)

SST fell from 13.9°C at station 39 to 13.4°C at station 41, rising again to 13.5°C at station 43. Allowing for the increase in surface temperature in the mixed water, seen in the previous transect, continuous surface monitoring places stations 39 & 40 in stratified water, and 41-43 in mixed. The vertical profile data (Figure 37) indicates that stations 39 & 40 were stratified and station 41 was becoming more mixed. Station 42 showed a deepening of the surface isothermal layer, and at station 43 the thermocline had strengthened again at 14-22m, despite the fact that the isotherms indicate a mixed water mass. Chl F values (Figure 37) were high above 25m at stations 39 & 40 in the stratified water, falling at station 41, and being very much lower at stations 42 & 43 in the mixed water mass.

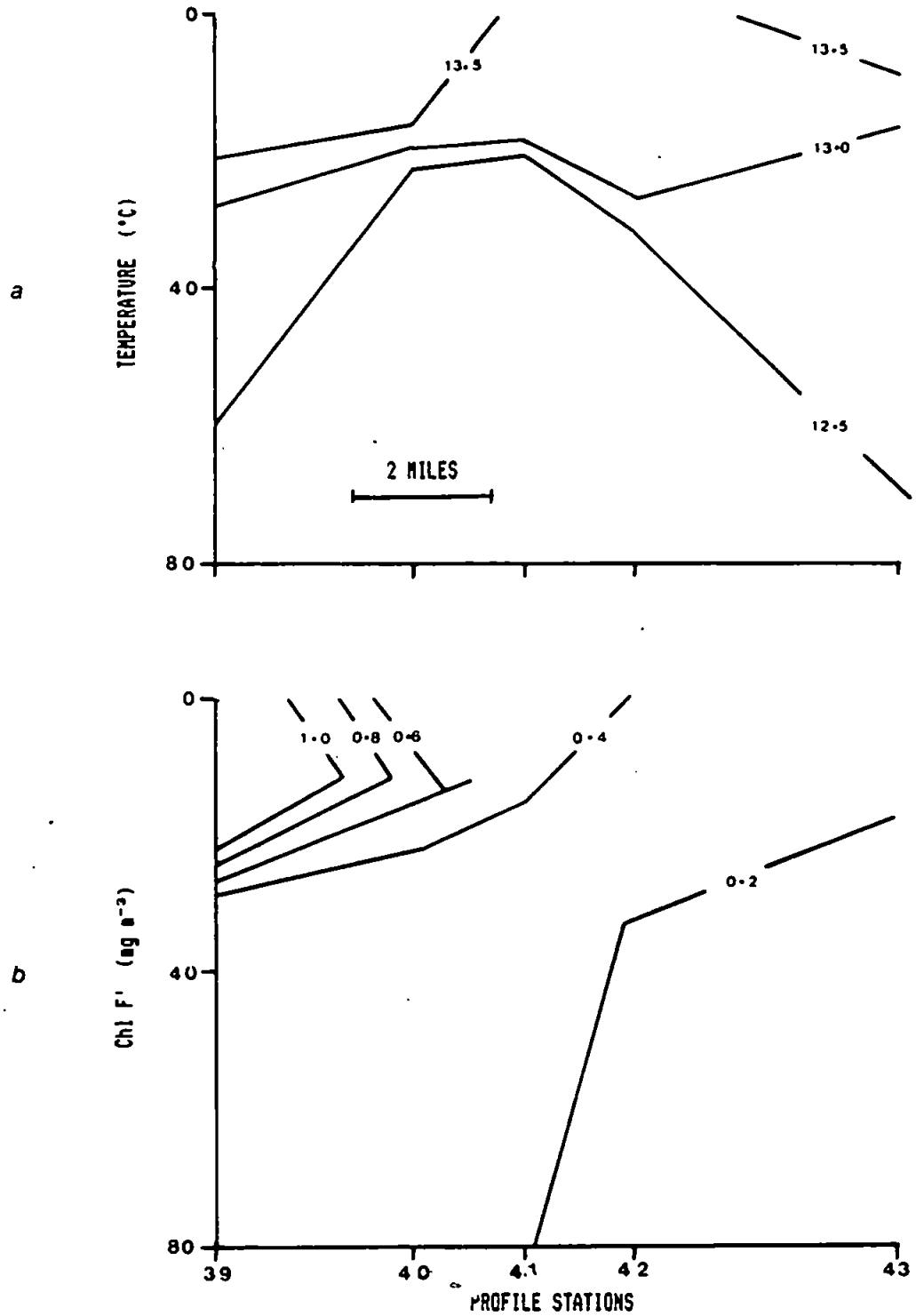


Figure 37. Ushant front, 24 June 1984. Transect 5, profile stations 39-43. Distribution of (a) temperature (°C) and, (b) Chl F' (mg m^{-3}) with depth.

(b) Distribution of Chl F', Chl S, log ATP and ph with depth.

The distribution of temperature, Chl F', Chl S, Log ATP and pH at 3m, 15, 24m, 30m and 50m for the five transects are presented in Appendix 2.

At 3m, temperature ranged from 12.8-14.1°C, being highest in the stratified water, but increasing from ≈12.8°C in the mixed water in the north to ≈13.5°C in the mixed water at the more southerly stations. At 15m, the temperature varied by >1.8°C, but showed no correlation with the mixed or stratified water masses. At 20m the temperature was higher at stations 36-43. This trend was more marked at 30m and again at 80m, although temperatures were slightly lower at stations 36-43 at 80m. A general increase in the temperature throughout the water column is seen in the more southerly transects.

Chl F' at 3m was highest (>0.5 mg m^{-3}) at stations 25-30 and 36-41, showing no correlation with either the mixed or stratified water. At 15m, Chl F' again showed no correlation with either water mass, reaching maximum concentrations(≈1.1 mg m^{-3}) at station 39. Chl F' at 20m was highest (≈0.9 mg m^{-3}) at stations 25-29 and 33-40. At 30m Chl F' (0.25-0.40 mg m^{-3}) showed little variation, although there was a slight increase at stations 36-40. At 80m Chl F' was relatively constant (≈0.2 mg m^{-3}).

Chl S at 3m varied throughout the transects (1.0-6.0 mg m^{-3}), showing no correlation with either water mass, but was generally lower at stations 32-43. At 15m, Chl S was again variable (1.3-4.5 mg m^{-3}), but was lower at stations 34-42. This trend was continued at 20m. Chl S was very variable on transects 1 & 2, but less variable on transects 3-5, with levels decreasing to the south of the survey area and showing no correlation with either water mass.

Log ATP at 3m, 15m & 20m showed no difference between mixed and stratified, varying from -6.0 to -3.0, but on average, values were lowest on transect 3. At 30m, values were highest at stations 21-25, lowest at stations 28-33 (transect 3) and increased again at stations 37-43. At 80m values were generally high (>-4.5), but fell at stations 17-20 and 26-29.

pH varied from 7.50- 8.10, and at 3m was lowest (7.60-7.90) south of station 29, but this pattern was not echoed at 15m. At 20m values were highest (7.80-8.05) at stations 16-29, increasing again at 33-42, then dropping again at station 43. This 20m pattern was repeated at 30m & 80m, although no correlation could be found between pH and any other parameters or between pH and the mixed or stratified water, the overall trend being lost in the noise of the signal.

(c) DCMU addition

The results of DCMU addition on *in vivo* chlorophyll fluorescence (Chl F) were not consistent, either between, or within water masses. Some typical depth profiles of Chl F (F-DCMU), DCMU-enhanced fluorescence (F+DCMU), Chl F' (chlorophyll *a* determined by fluorometric methods) and Chl S (chlorophyll *a* determined by spectrophotometric methods) are shown in Figure 38.

At station 23 (1520h), in stratified water, the thermocline (13.9-12.0°C) was at 16-20m. Although DCMU addition enhanced fluorescence emission in all samples, F+DCMU did not reflect Chl S levels any more accurately than did F-DCMU or Chl F'. The effects of DCMU addition were greatest above the thermocline at 6-16m.

At station 28 (also in stratified water), at 0200h, the thermocline (13.5-12.0°C) was at 15-20m. At night, with no photosynthesis taking place, it was thought that DCMU addition would have little effect on fluorescence emission. At 6m this was indeed the case, with F+DCMU and F-DCMU having the same value, although at 10m F+DCMU was lower than F-DCMU. Below 10m, however, DCMU enhanced fluorescence in all samples.

At station 29 (0400h), in the mixed water mass, DCMU enhanced fluorescence emission in all samples, although the effect was greatest at 30m, and F+DCMU showed no greater correlation with Chl S than did F-DCMU.

At stations 32 (0920h, mixed water mass) and 36 (1800h, mixed water mass) F+DCMU and F-DCMU both correlated well

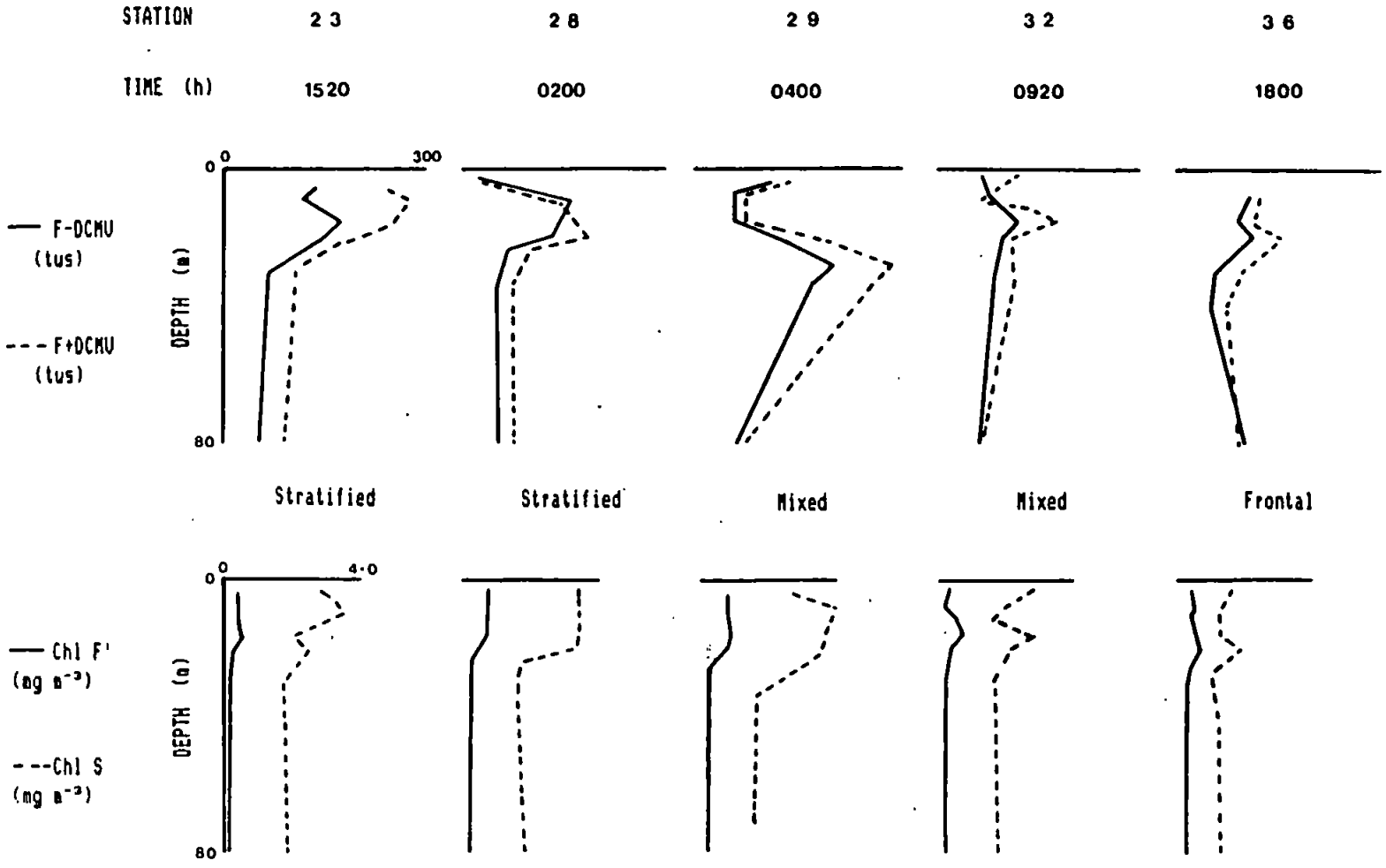


Figure 38. Typical profiles of Chl F', Chl S, F-DCMU and F+DCMU for mixed and stratified water masses across the Ushant front.

with Chl S. DCMU enhanced fluorescence at most sample depths, the exceptions being at 10m and 80m at station 32, and at 80m at station 36.

(d) Tidal corrections

An interesting feature to emerge in this series of North - South transects of the Ushant Front is the effect of tidal motion on the position of the front. The tidal currents in this area produce a kidney-shaped tidal ellipse which is approximately 7.7 miles in its longest dimension, oriented almost east - west. Figure 32(b) shows the position of the front relative to the water masses when tidal corrections are taken into account.

The effect of tidal motion during the East - West transects, which were taken slightly north and east of the first series of transects had much less effect on the position of the front, since the tidal ellipse was much smaller, being only 1 mile by 2.5 miles, oriented northeast - southwest.

5.3.3. East/West Transects (Figure 39)

The series of east/west transects across the front were taken on the 25 - 27 June. Temperature, Chl F and pH at 3m are shown in Appendix 2.

Transect 1 (Stations H15 - 46, Figure 40):

SST rose steadily from west to east, from 14.4°C at station HH15 to 14.9°C at station 46, with the temperature at 70m rising from 12.1°C to 13.2°C, resulting in a general weakening of the gradient across the thermocline (2.0-0.6°C) from west to east. Sea surface monitoring placed all stations in mixed water. The vertical profile data, however indicated a degree of stratification at stations HH15 to 45, with station 46 becoming more well-mixed. However, since stratification is not as pronounced as that found in other transects, this water mass will be referred to as the mixed water mass.

Chl F' ranged from 0.11-0.48 mg m^{-3} at station HH15 (with a maximum at 5-10m), increasing to 0.11-0.86 mg m^{-3} at stations 44 and 45, where values were generally higher throughout the top 30m of the water column, with the maxima associated with the slight strengthening of thermocline. The distribution of Chl F' at station 46 was similar to that at the western edge of the transect (0.11-0.43 mg m^{-3}).

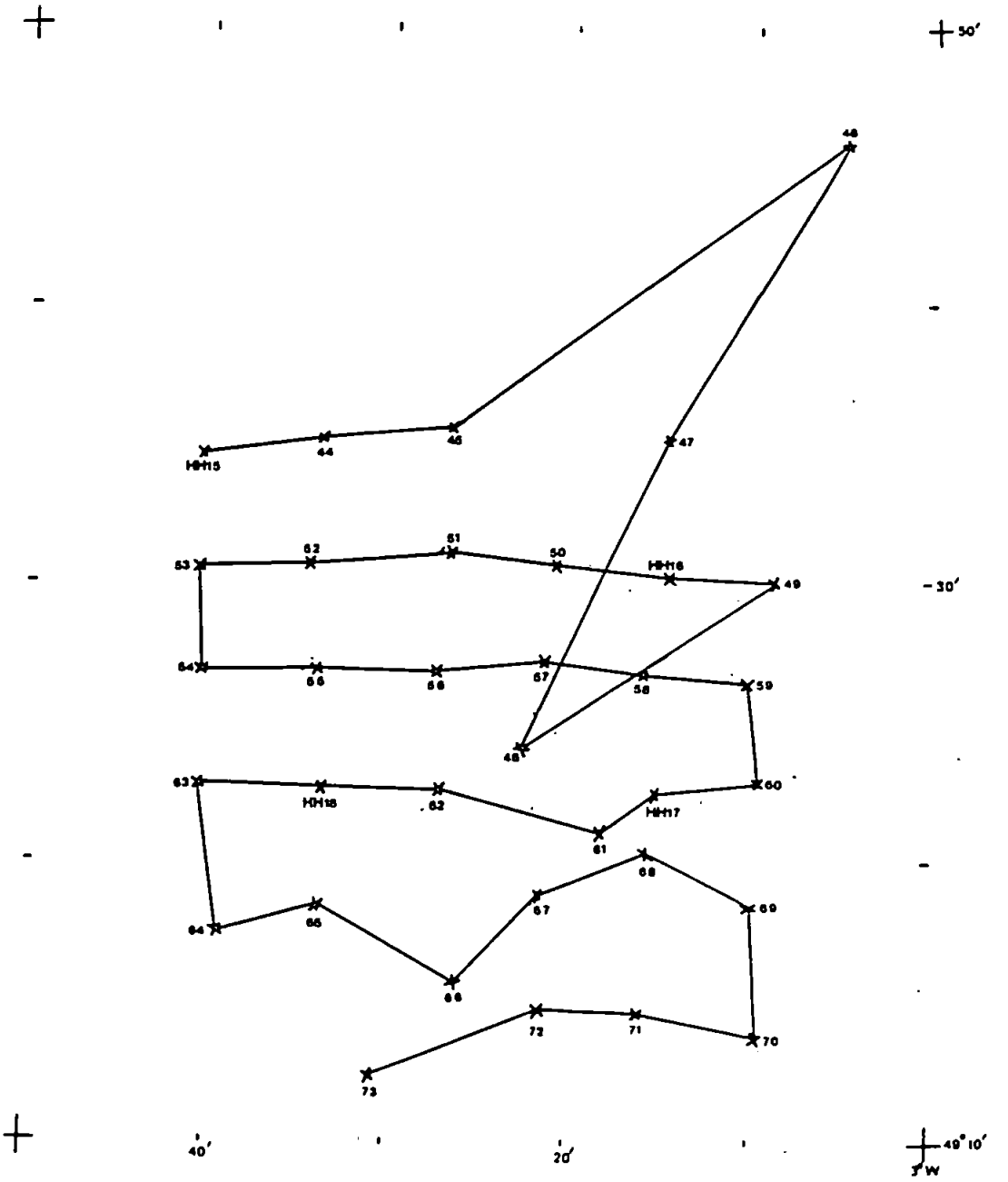


Figure 39. East/west transects of the Ushant front, 25-27 June 1984. Ships track and profile stations HH15 to 73.

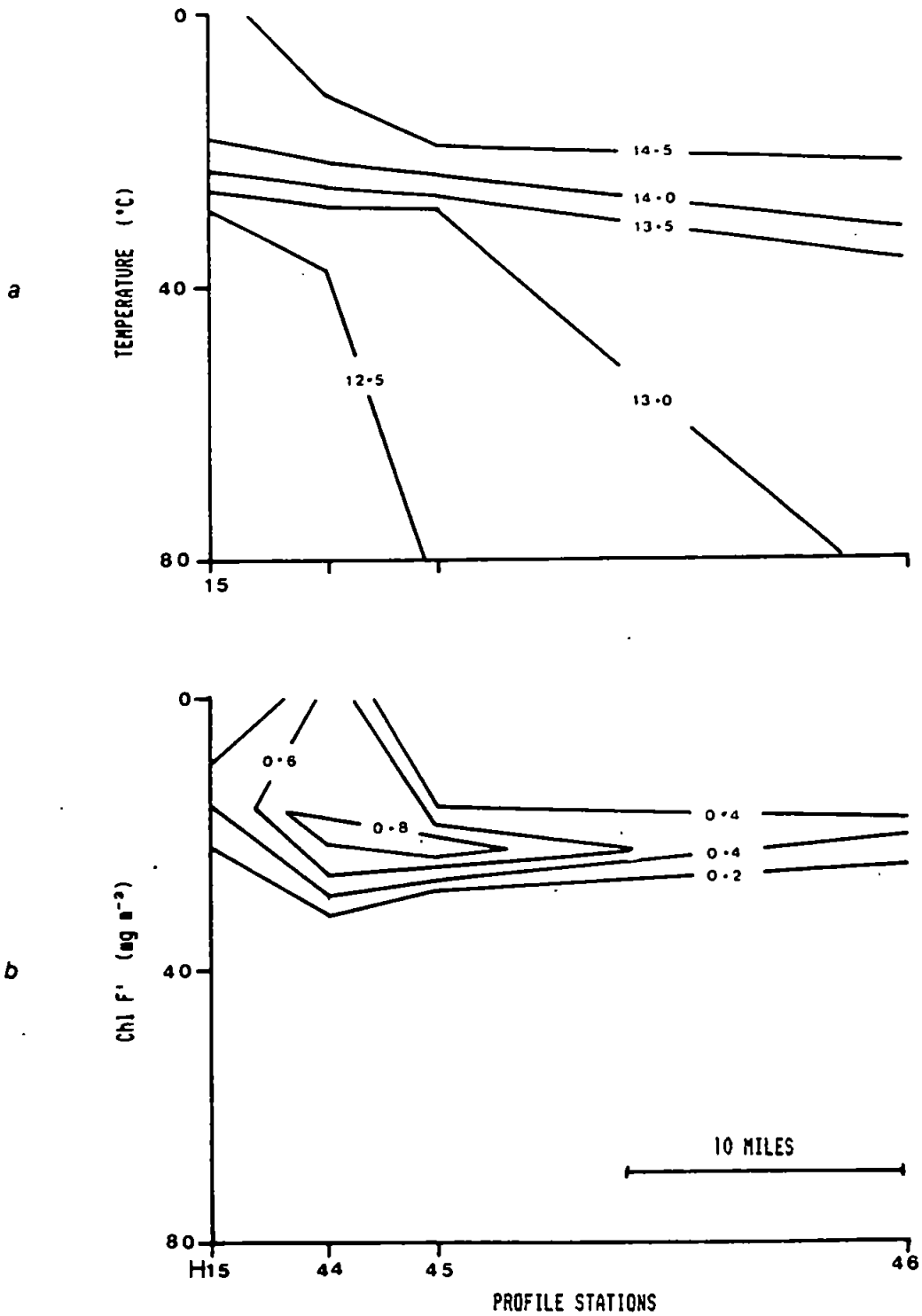


Figure 40. Ushant front, 25 June 1984. Transect 1, profile stations HH15 to 46. Distribution of (a) temperature (°C) and (b) Chl F' (mg m^{-3}) with depth.

Transect 2 (Stations 49 - 53, Figure 41)):

The continuous surface monitoring data (Appendix 2) indicated that station 49 was in stratified water, H16 in mixed, 50 was at the front, 51 & 52 were in stratified water again, and station 53 was frontal. SST was highest at the western edge of the transect (17.0-17.4°C at stations 51 to 53, decreased to 14.4°C at station 50, then increased again to 16.3-16.5°C at stations HH16 and 49. The 70m temperature fell from approximately 14.8°C at stations 51 to 53, to 12.5°C at station 50, then rose again to 14.4°C at stations HH16 and 49 at the eastern edge of the transect. The vertical profile data (Figure 41) indicated that station 49 was stratified, H16 frontal, station 50 mixed, 51 frontal, and 52 & 53 were stratified again.

Chl F' values were highest (1.10, 0.66 mg m^{-3}) at the two stations to the west of the cold water intrusion (stations 51 & 52), decreasing to 0.10-0.42 mg m^{-3} at station 53 at the western edge of the transect. At station 50, in the colder water mass, values were very low (0.10-0.29 mg m^{-3}), and at the two stations east of station 50 (HH16 & 49), Chl F' distribution was similar to that in the west, ranging from 0.10-0.42 mg m^{-3}, with the highest values being associated with the thermocline at 20-30m.

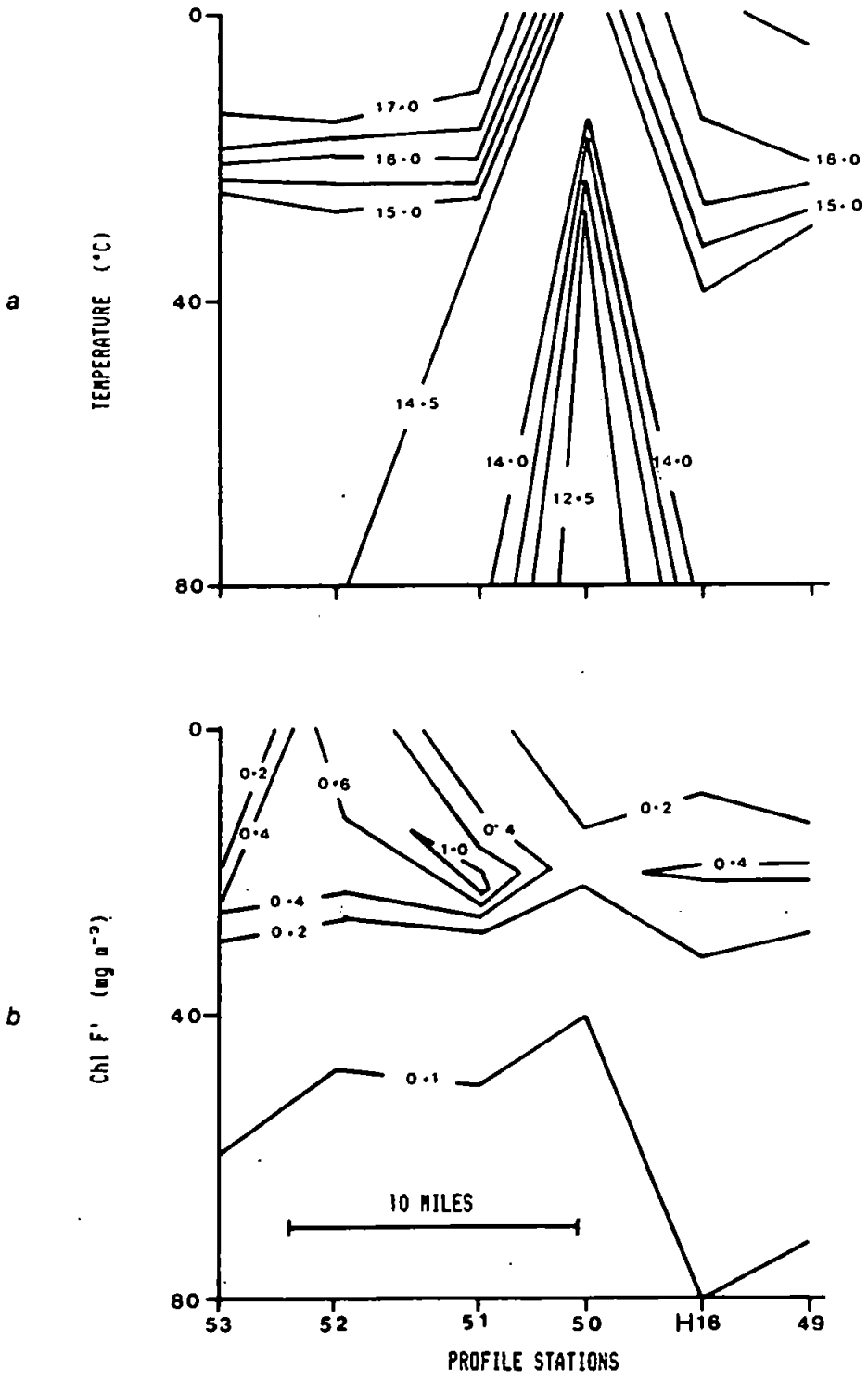


Figure 41. Ushant front, 25 June 1984. Transect 2, profile stations 49 to 53. Distribution of (a) temperature (°C) and (b) Chl F' (mg m^{-3}) with depth.

Transect 3 (Stations 54 - 59, Figure 42):

The continuous surface monitoring data indicated that station 54 was in stratified water, 55 at the front, 56 & 57 were in mixed water, and stations 58 & 59 were frontal. SST decreased from 17.0°C at station 55 to 14.8°C at station 58, rising again to 16.8°C at station 59. No temperature data are available for stations 54, 56 & 57. The vertical profile data indicates that 55 was in stratified water, 58 was frontal, becoming mixed, and station 59 was stratified / frontal.

Chl F' values were relatively high above 20m at station 54 (0.40-0.51 mg m^{-3}), falling to 0.10-0.35 mg m^{-3} at station 55. Values were lowest at stations 56 and 57 in the mixed water (0.10-0.17 mg m^{-3}), rising slightly to 0.10-0.25 mg m^{-3} at station 58, and were highest at station 59 (0.10-0.62 mg m^{-3}), where there was a pool of high chlorophyll at 10-25m.

Transect 4 (Stations 60-63, Figure 43):

SST rose from 14.8°C at the west of the transect (station 63) to 16.0°C at station 62, then fell to 15.0°C at station 61. SST then rose again to 15.4°C at HH17, before dropping slightly to 15.2°C at station 60 at the eastern edge of the transect. The vertical profile data indicated that station 63 was in mixed water, HH18 & station 62 were in stratified, and station 61 was tending towards mixed again. At HH17, although SST was lower (15.4°C) than at stations 62 and HH18, stratification was

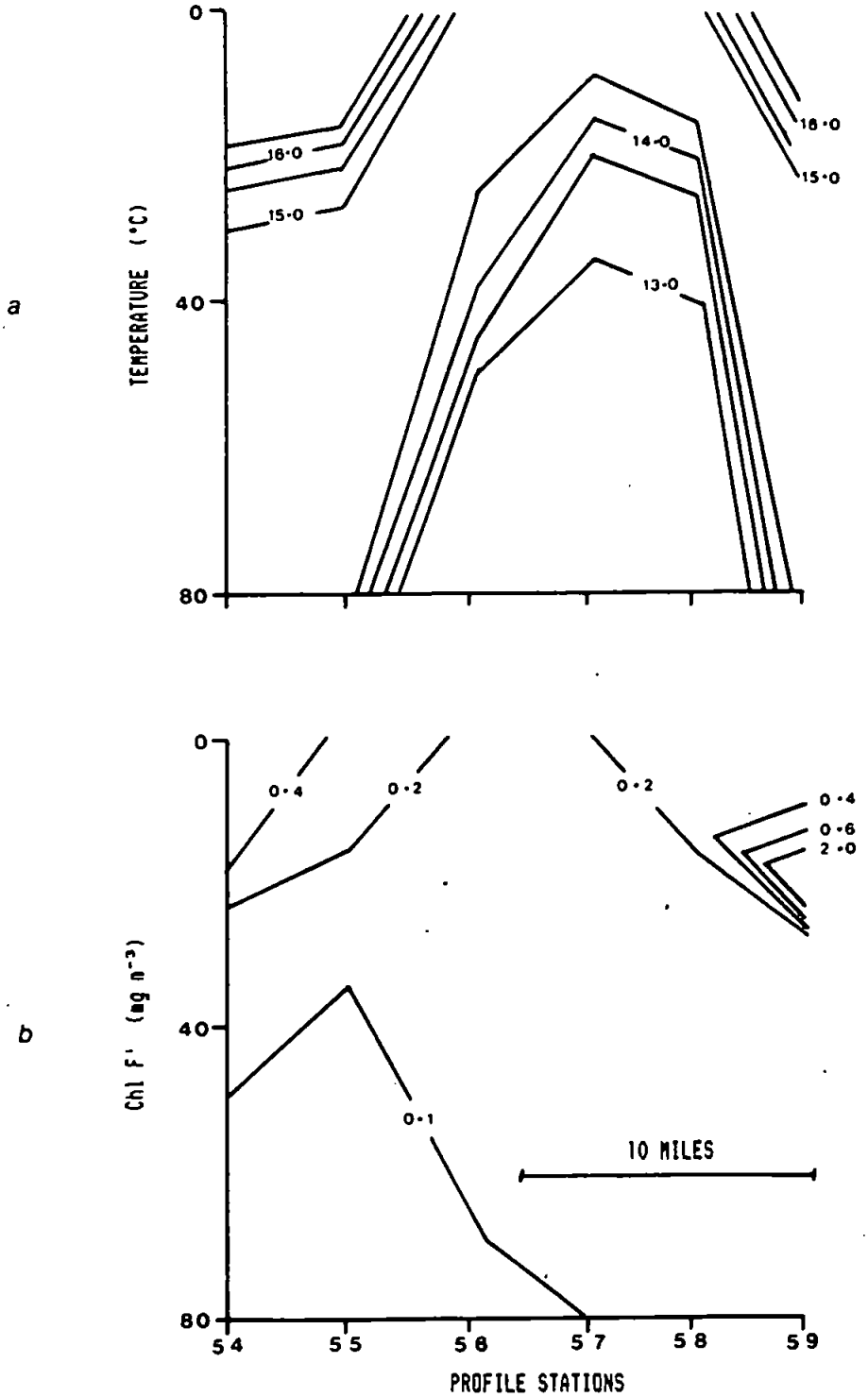


Figure 42. Ushant front, 26 June 1984. Transect 3, profile stations 54 to 59. Distribution of (a) temperature (°C) and (b) Chl F' (mg m^{-3}) with depth.

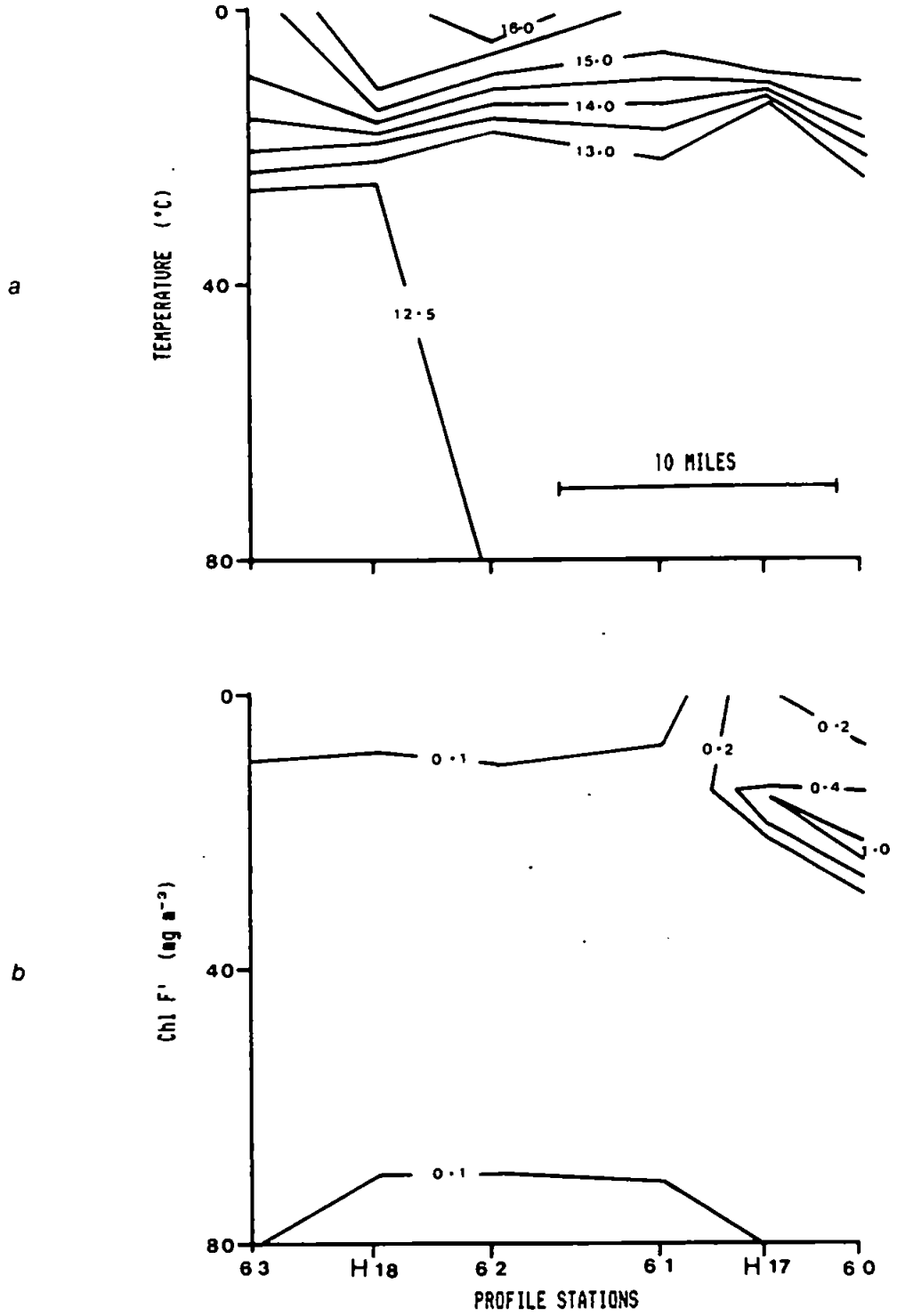


Figure 43. Ushant front, 26 June 1984. Transect 4, profile stations 60 to 63. Distribution of (a) temperature (°C) and (b) Chl F' (mg m^{-3}) with depth.

more pronounced. At the eastern end of the transect (station 60), the water column was again becoming more mixed. The sea surface monitoring programme, however, indicates that the front was crossed 8 times on this transect.

Chl F' was very low (0.05-0.19 mg m^{-3}) at the western end of the transect (stations 61-63), but at the eastern end (stations HH16 & 60) values were very much higher (0.1-1.75 mg m^{-3}), with a pool of high chlorophyll at 15-25m. Chl F' was also high at the stations immediately north and south of station 60.

Transect 5 (Stations 64-69, Figure 44):

SST at the western end of the transect (station 64) was 15.4°C, falling to 15.0°C at stations 65 and 66, then rising again to 15.3°C at stations 67 to 69. Despite the higher SST at station 64, the water column was almost as well-mixed as at stations 65 and 66. Stations 67 to 69 were all in stratified water, with stratification becoming more pronounced at the eastern end of the transect.

Chl F' at station 64 ranged from 0.11-0.37 mg m^{-3}, being 0.11 mg m^{-3} (minimum) from 0-8m, then increasing to maximum (0.37 mg m^{-3}) at 16-30m, below the base of the thermocline, and remaining constant at around 0.25 mg m^{-3} from 40-70m. At stations 65-67, values were very low throughout the water column (<0.13 mg m^{-3}), increasing slightly (0.10-0.29 mg m^{-3}) at station 68, but were very much higher at station 69 (0.13-0.98 mg m^{-3}), with a pool

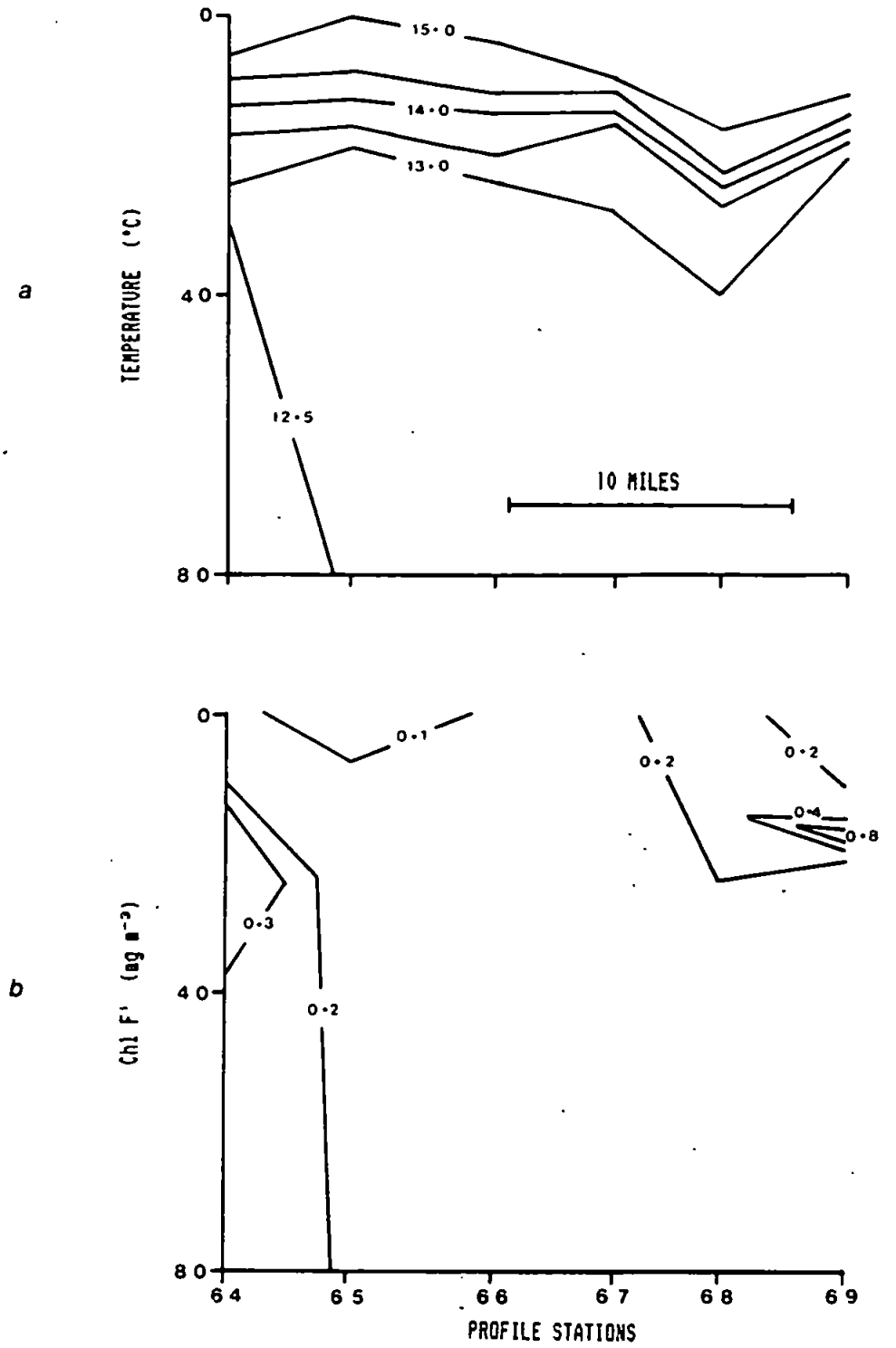


Figure 44. Ushant front, 27 June 1984. Transect 5, profile stations 64 to 69. Distribution of (a) temperature (°C) and (b) Chl F' (mg m^{-3}) with depth.

of high chlorophyll associated with the base of the thermocline at 14-20m.

Transect 6 (Stations 70-73, Figure 45):

SST decreased from 15.8°C at the western end of the transect (station 73) to 15.3°C at station 72, increasing again to 15.8°C at station 71, then decreasing slightly to 15.6°C at station 70 in the east. The vertical profile data indicated that station 73 was frontal, station 72 mixed, station 71 was in stratified water (with the development of a surface isothermal layer), and that at station 70, at the eastern end of the transect, the water column was again becoming more mixed.

Chl F' was very low (0.10-0.18 mg m^{-3}) at stations 73 and 72 (in the west). Values at stations 71 and 70 were slightly higher, ranging from 0.10-0.37 mg m^{-3}, with a pool of chlorophyll (>0.3 mg m^{-3}) associated with the thermocline at 12-20m.

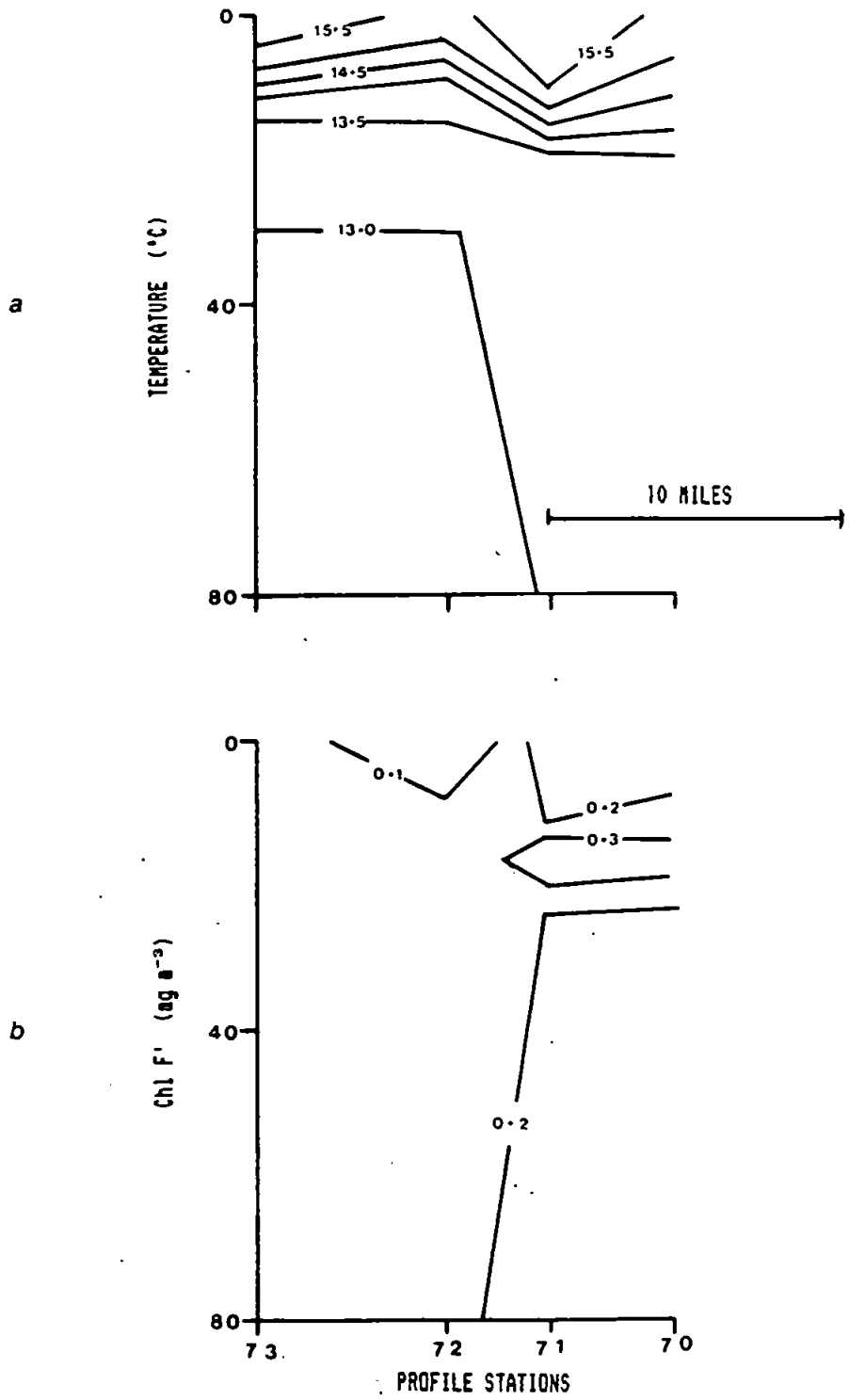


Figure 45. Ushant front, 27 June 1984. Transect 6, profile stations 70 to 73. Distribution of (a) temperature (°C) and (b) Chl F' (mg m^{-3}) with depth.

5.4. SATELLITE DATA

Infra-red (IR) satellite imagery from TIROS N-7, where the darkness of the image increases in proportion to the radiation temperature (Plates 2 to 6), illustrates the movement of the Ushant front about its mean position for the period 8 to 28 June 1984.

At 1433 GMT 8 June (Plate 2) the front is very close to the French coast, with finger-like patterns produced by baroclinic instabilities which more usually result in the formation of frontal eddies.

By 0807 GMT 9 June (Plate 3), however, the front has moved further off the French coast, with a pool of warm water evident to the west of Guernsey.

At 1435 16 June (Plate 4), three days after Mean High Water Spring (MHWS) tide, when tidal mixing processes are at their most intense, the front has moved significantly. It is now much further off the French coast, almost level with Guernsey. However, due to cloud cover, it cannot be discerned whether the warm water feature which had developed off Guernsey on 9 June is still evident.

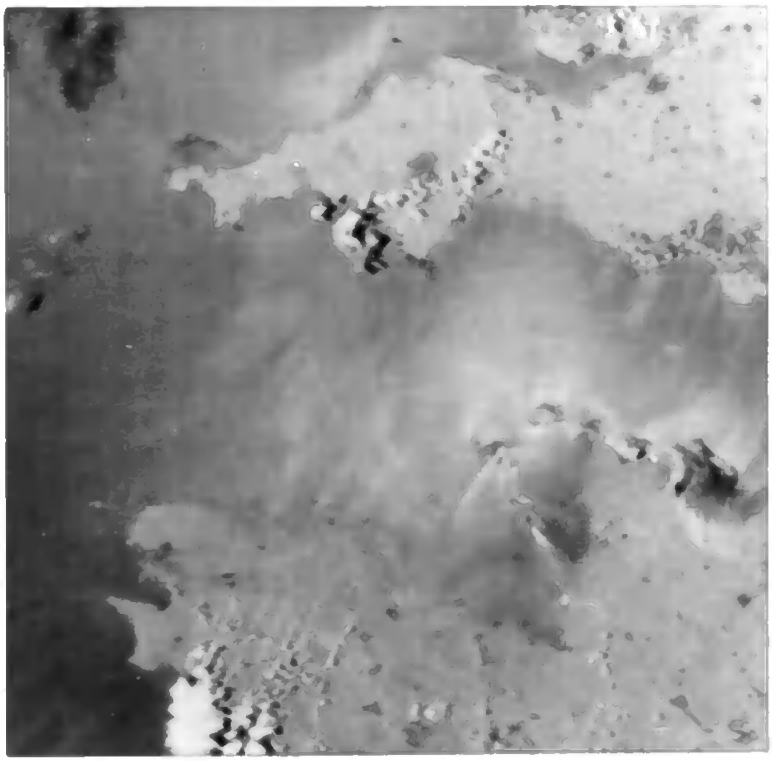
The front was hardly detectable by IR imagery for the period 17 to 27 June (when the depth profiles were taken) due to sea mist and more general cloud cover, but by 1529

GMT 28 June (Plate 5) the front is almost as close to the French coast as it was on 8 June, with the 'fingering' now extending to the south and west of Guernsey. By 1516 GMT 29 June (Plate 6), this 'fingering' has developed into a much larger-scale feature, and the front has again moved further off the French coast.

PLATE 2.

TIROS N-7 (a) visible and (b) infrared images of the Ushant front, 8 June 1984. Received and enhanced by the University of Dundee.

a



b

PLATE 2

PLATE 3.

TIROS N-7 (a) visible and (b) infrared images of the Ushant front, 9 June 1984. Received and enhanced by the University of Dundee.

a

b

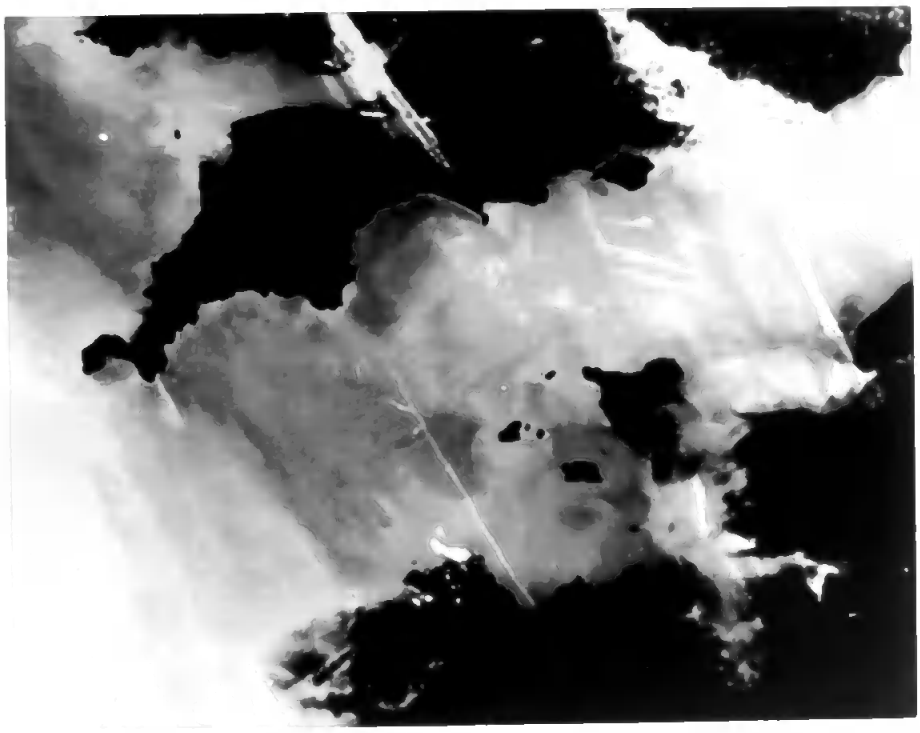


PLATE 3

PLATE 4.

TIROS N-7 (a) visible and (b) infrared images of the Ushant front, 16 June 1984. Received and enhanced by the University of Dundee.

a

b

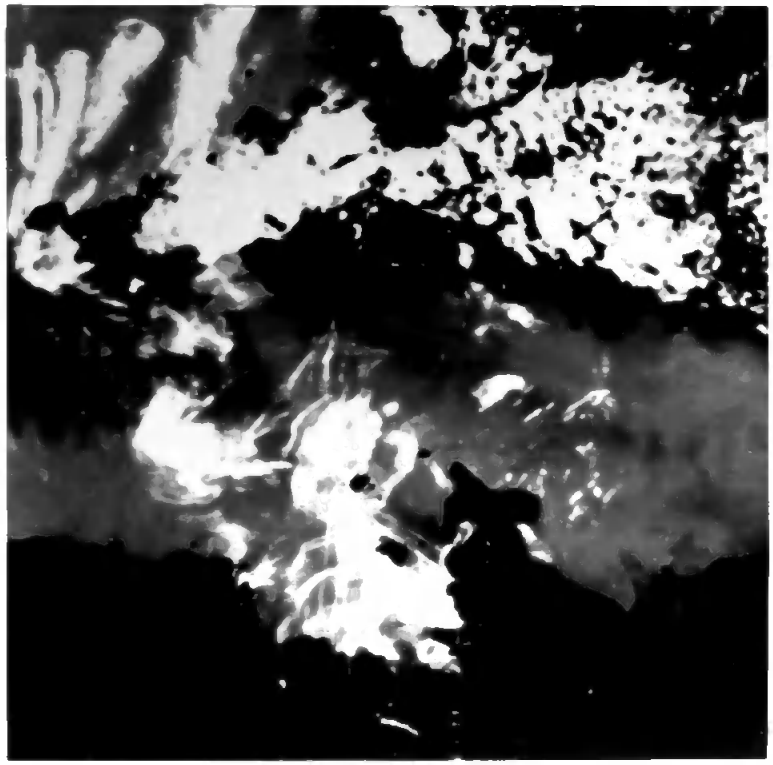
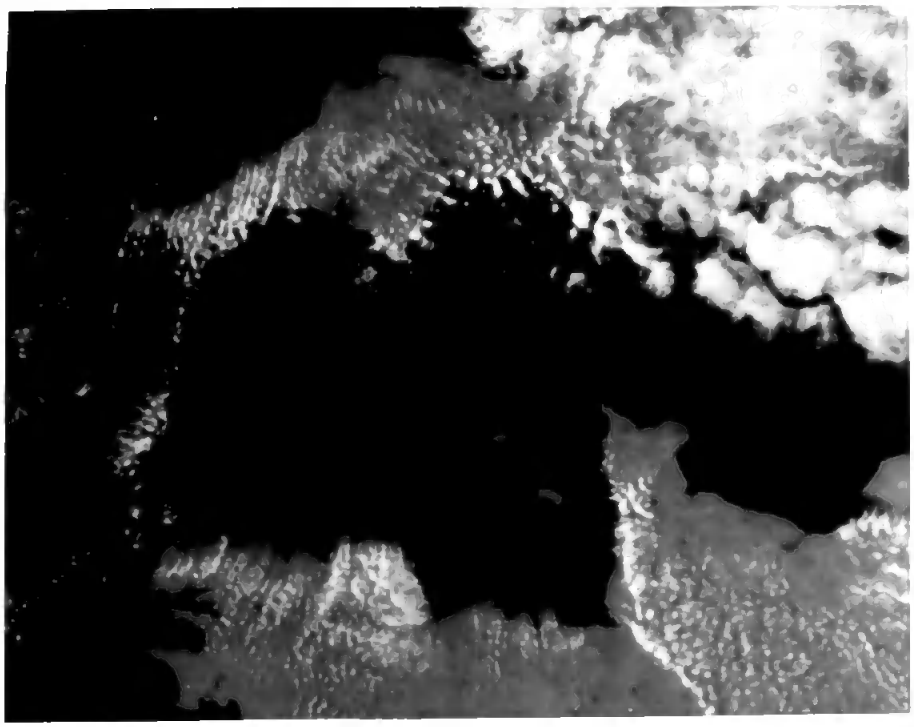


PLATE 4

PLATE 5.

TIROS N-7 (a) visible and (b) infrared images of the Ushant front, 28 June 1984. Received and enhanced by the University of Dundee.

a



b

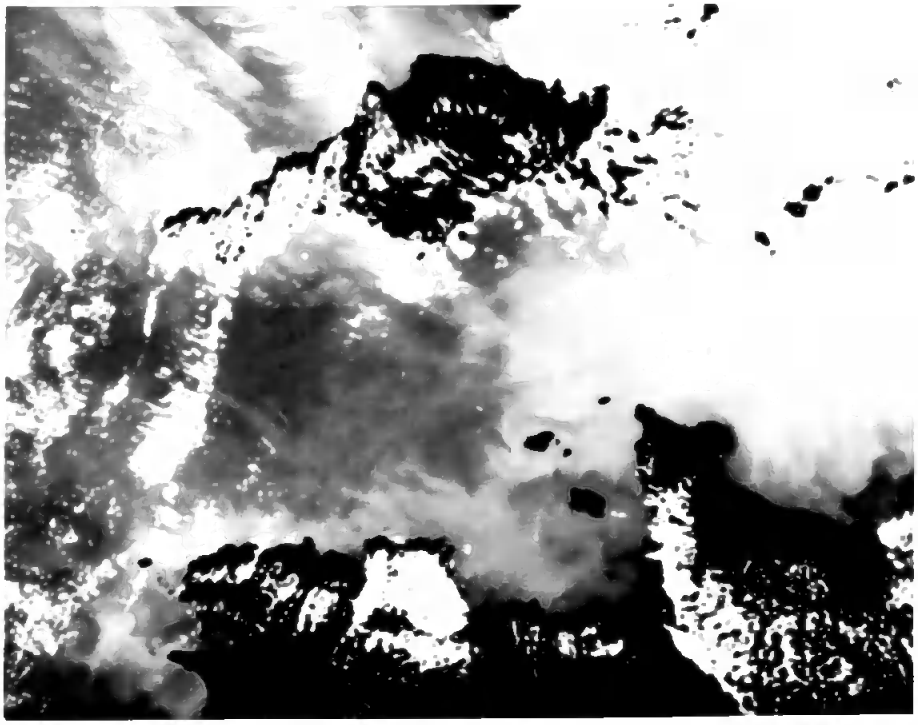
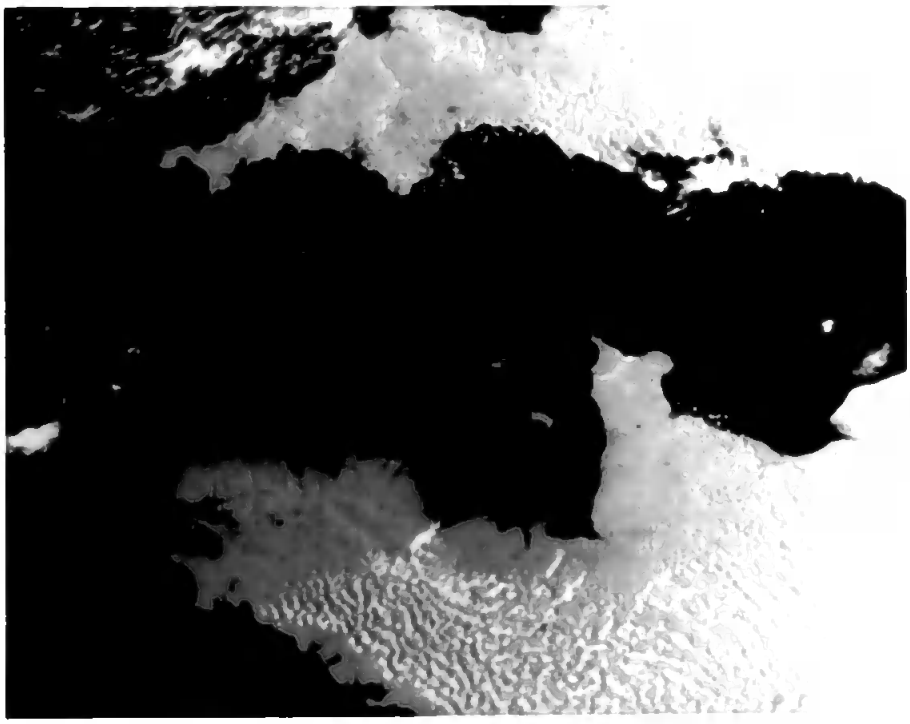


PLATE 5

PLATE 6.

TIROS N-7 (a) visible and (b) infrared images of the Ushant front, 29 June 1984. Received and enhanced by the University of Dundee.

a



b

PLATE 6

5.5. DISCUSSION

5.5.1. Rates of change in surface parameters

5.5.1.(i) Temperature.

On 13 June, a 0.5% rate of change in temperature (T1) detected all 8 crossings of the front, but only 9 of the 10 skirtings, with no false alarms.

When the sensitivity was raised to a rate of change of 0.1% (T2), 50% of the total number of alarms flagged by T2 occurred in advance of T1. At this lower rate of change, 40% of all flags raised by T2 were designated as false since they did not occur in a region of temperature change.

However, if the number of false alarms raised by T2 is disregarded, then the percentage of flags raised in advance of T1 rises to 83%.

The high rate of T2 false alarms was due to the fact that alarms were flagged almost continuously. It is therefore possible that some of the alarms counted as occurring in advance of T1 were not "true" alarms, but merely a function of the high rate of flagging. If this is the case then the rate of false alarms raised by T2 must be much higher than the estimated 40%, and this could also significantly reduce the distance advantage of 1 to 5 miles given by T2 over T1.

5.5.1.(ii) Chl F.

At a rate of change of 10.0% (C1), Chl F detected 100% of all crossings and skirtings, 78% of the detections being in advance of T1 (by 0.5 to 2.0 miles), with no false alarms.

When the sensitivity was raised to a rate of change of 5.0% (C2) all crossings and skirtings were again detected, with 76% of the alarms being raised in advance of T1 and the distance advantage increasing to 0.5 to 5.0 miles. This fall in the percentage of alarms flagged before T1 was due to an increase in the false alarm rate to 14%. If the number of false alarms is disregarded, however, the percentage of flags raised in advance of T1 rises to 89%.

As in the case of T2, the designation of alarms as false is again difficult, but for different reasons. For example, the C2 alarm at approximately 0815h, 13 June (Figure 28), has been designated as false as it does not occur in proximity to a well-defined crossing or skirting of the front. It is, however, associated with a very slight temperature variation which was not detected by T1, and could, therefore, equally well be taken to be an indication of the proximity of another water mass, rather than a false alarm.

5.5.1.(iii) pH.

pH1 (0.4%) detected 63% of the crossings and 30% of the skirtings, the false alarm rate being 33%, with 25% of the detections occurring 0.5 to 1.5 miles in advance of T1.

pH2 (0.3%) detected 75% of crossings and 40% of skirtings, with a false alarm rate of 33%. The percentage of alarms raised in advance of T1 rose slightly to 27%, and the distance advantage increased to 0.5 to 2.0 miles.

Increasing the sensitivity of this parameter by lowering the rate of change below 0.3% did not improve the percentage of detections, but merely resulted in an increase in the false alarm rate.

5.5.1.(iv) False Alarms.

As previously stated, the designation of any single alarm, or block of consecutive alarms, as false was sometimes difficult. Consequently, the figures quoted must contain a high degree of subjectivity.

In the case of temperature, decreasing the rate of change (i.e. increasing the sensitivity) resulted in an apparent increase in the distance advantage gained.

However, as the sensitivity was increased, flags were raised at almost every data point, giving rise to a high rate of false alarms (50%). Therefore, some of the alarms occurring in a region of temperature change must also be suspected of being false alarms. This would obviously affect the apparent distance advantage given by T2 over T1 as the percentage of alarms in advance of T1 would be lowered because of the increase in false alarms.

The problem of classifying the flags raised by the rate of change in Chl F (C1 and C2) was, however, of a different nature from that affecting the temperature data. In this case, the difficulty of designating alarms as "real" or "false" arose from the fact that both C1 and C2 flagged alarms in areas where T1 did not detect any major temperature change. However, on the majority of occasions when this occurred, alarms were associated with very slight temperature changes, an example of which was discussed above. These flags may therefore not in fact be "false" alarms at all, but an indication of the proximity of a front which has not, as yet, been detected by temperature.

This would appear to be a likely interpretation, since the results for C1 indicate a high percentage (78%) of detections occurring in advance of T1.

When the sensitivity was increased to a rate of change of 5.0% (C2), the number of detections in advance of T1 fell slightly to 76% due to the apparent increase in the

false alarm rate from 0 to 14%. However, if some of these alarms are not in fact false, but are warnings of a nearby frontal system, then the actual false alarm rate would be lower. The efficiency of using the rate of change in Chl F to give advance warning of an approaching frontal region would, therefore, be enhanced by using the lower, more sensitive rate of change.

In the case of pH, increasing the sensitivity from a rate of change of 0.4% to 0.3% raised the detection rate of crossings from 63 to 75%, and of skirtings from 30 to 40%, but did not increase the rate of false alarms.

As with C1 and C2, some of the false alarms were associated with slight temperature changes which were not detected by T1 (e.g, 0815h 13 June, Figure 28), and the same arguments as to whether these alarms should be categorised as real or false must be applied.

However, pH1 and pH2 flagged far fewer alarms in advance of T1, with a much higher false alarm rate, than did C1 and C2. Also, if the sensitivity of the rate of change in pH was raised beyond 0.3%, alarms were flagged in what appeared to be a random pattern, bearing little relation to either large or small variations in temperature. On these grounds, therefore, the argument that some of the alarms designated as false are actually indications of the proximity of another water mass, would not appear to be as strong for pH as for Chl F.

5.5.2. Depth Profiles

5.5.2.(i) Temperature and Chl F' across the front

The North/South transects (Figure 32: 49°N, 3°45'W; 49°25'N, 4°W) showed a transition from stratified to well-mixed water, with both SST, and the temperature differential over the water column (0-80m), decreasing to the south of the survey area.

On transect 1 (Figure 33), the highest Chl F' values (0.6-0.8 mg m^{-3}) were associated with the thermocline (≈20m) at the most strongly stratified station at the north of the transect (station 16).

On transect 2 (Figure 34), the Chl F' maximum (0.6-0.8 mg m^{-3}) was at 0-20m at the mixed and frontal stations, and on transect 3 (Figure 35)Chl F' values were highest (0.6-1.0 mg m^{-3}) at 0-20m in the mixed water at station 29, falling to a maximum of 0.4-0.6 mg m^{-3} at stations 32 and 33 (also in the mixed water mass).

On transect 4 (Figure 36), however, high Chl F' levels (0.6-1.2 mg m^{-3}) were found at around 20m in both the stratified and mixed water masses (stations 34, and 36-38), but were not consistent throughout the transect, falling to 0.4-0.6 mg m^{-3} at 20m at station 35 in the stratified water.

Chl F' values on transect 5 (Figure 37)were highest (0.4-1.2 mg m^{-3}) at 0-30m in the stratified water at station 39, decreasing to 0.4-0.8 mg m^{-3} at 0-20m at station 40 (also in the stratified water), then decreasing

steadily throughout the water column at stations 41-43 in the mixed/frontal areas.

The structure of the water column on the East/West transects (49°10'N, 3°W; 49°40'N, 3°50'W) was rather more complex than that of the North/South transects, as there was some degree of stratification evident at most of the profile stations. However, there were two distinct water masses - one with a SST of 14.0-15.0°C, and the other (where stratification was much more pronounced) with a SST >16.0°C. Although the 0-80m temperature differential of the former was similar to that of the stratified stations on the North/South transects, the water column was not as strongly stratified, and is referred to as the mixed water on the East/West transects

On transect 1 (Figure 40), all stations were in the mixed water mass, with a slight strengthening of the thermocline at station 45. Chl F' values were highest at station 44, ranging from 0.6-1.0 mg m^{-3} at 0-20m, with a Chl F' maximum at about 20m at all stations.

On transect 2 (Figure 41), both the stations at the west and east of the transect were strongly stratified, with a cold water intrusion at station 50; Chl F' values were lowest in the mixed water at station 50, and highest (>1.0 mg m^{-3}) at around 20m in the stratified water at station 51.

On transect 3 (Figure 42), the cold water intrusion was evident at stations 56, 57 and 58, and again associated with the lowest Chl F' values (≤0.2 mg m^{-3}). The highest Chl F' values (0.6-2.0 mg m^{-3}) were found at the thermocline in the stratified water at the east of the transect (station 59).

On transect 4 (Figure 43), the temperature profiles changed markedly, and although not well-mixed, showed no surface isothermal layer, but a steady decrease in temperature over the top 20m of the water column. Sea surface temperature monitoring (Appendix 2: 26 June, 1200-2400h), however, indicated that profile stations HH17, 61, 62, HH18 and 63 were all taken at points of advection between water masses, which was probably responsible for the peculiar temperature profiles. Chl F' values were very low (0.0 to <0.2 mg m^{-3}) at stations 61-63. This could also have been a consequence of the rapid advection of the two water masses at these profile stations, since Chl F' values were much higher (0.1-1.2 mg m^{-3}) at stations 60 and HH16, where the sea surface monitoring data (Appendix 2) indicates no such marked advection.

On transect 5 (Figure 44), stations 64-66 were in mixed water, and stations 67-69 in stratified. Chl F' values were low (≤0.3 mg m^{-3}) in the mixed water at the western end of the transect and at stations 67 and 68 in the stratified water. At station 69, however, there was a

pool of high chlorophyll (0.6-1.0 mg m^{-3}) associated with the thermocline.

On transect 6 (Figure 45), Chl F' was uniformly low (0.1 mg m^{-3}) at stations 73 and 72, with slightly higher values (≈0.3 mg m^{-3}) associated with the thermocline at stations 70 and 71.

5.5.2.(ii) Correlation of Chl F', Chl S, ATP and pH with mixed and stratified water masses

Chl F' maxima were often, though not always (e.g. stations 28, 39, 54, 67), associated with the thermocline, in contrast with the results of Pingree *et.al.*, (1976) and Aiken & Taylor (1984), who have reported chlorophyll thermocline maxima over the whole stratified area of the continental shelf. However, Chl F' maxima were also found in the mixed water at around the same depth as the thermocline of the stratified water (e.g. stations 37 & 38).

In both the North/South and East/West transects, Chl F' showed no correlation with either water mass, or with the frontal region.

The lack of correlation between Chl F' and specific water masses is not, perhaps, surprising, since this was also found to be the case in the surface monitoring programme, where it was the *rates of change* in Chl F in

the vicinity of the front which were found to be critical, rather than absolute levels.

Although the results of this study give no firm indication that Chl F' can be used as a means of detecting the subsurface position of a front, the possibility cannot be ruled out. The rapid advection of the two water masses on the East/West transect 5 indicate that insufficient depth profile data were collected to estimate the rates of change in Chl F' between profile stations.

Such a calculation would require continuous fluorescence measurements over the water column on a transect between the two water masses. One possible method for making measurements of this sort may be the use of an undulating oceanographic recorder (Aiken & Taylor, 1984), although this also poses problems due to the way the instrument samples over the water column.

A similar lack of correlation was found between ATP (Appendix 2) and either water mass, or the frontal region.

It is, of course, possible that the same arguments which have been applied to Chl F' distribution may also apply to ATP. However, since continuous monitoring techniques already exist for chlorophyll fluorescence, but not for ATP estimations, it is unlikely that the development of this method as a real-time detection method would prove more profitable than the use of Chl F', or of Chl F.

pH measurements (Appendix 2) also showed no correlation with either water mass at any depth, although the surface monitoring programme indicated some potential as an advance warning technique. However, it is likely that the variations in pH which appear to occur in the vicinity of frontal regions are local peturbations brought about as a consequence of biological activity, and that no advantage is likely to be gained by using pH (in preference to Chl F) to detect either surface, or subsurface, fronts.

5.5.1.(iii) DCMU-enhanced fluorescence

In contrast to the findings of Slovacek & Hannan (1977), the results of the present study indicate that, in natural marine phytoplankton populations, DCMU addition does not give maximal *in vivo* fluorescence yields which are a constant function of cellular chlorophyll *a*.

Although F+DCMU was enhanced in the majority of samples, F+DCMU did not always show a better correlation with Chl S than did F-DCMU, and in some cases, the correlation between fluorescence and Chl S was actually reduced. The degree of correlation between F+DCMU and Chl S did not appear to be a function of temperature, nutrient status or of the light/dark cycle. In addition, the distribution of F+DCMU throughout the water column showed

no correlation with either the mixed or stratified water mass. It would not appear, therefore, that the addition of DCMU is likely to improve the degree of advance warning given by Chl F on approaching a front.

The possibility must also be considered that the very factors which affect the fluorescence:chlorophyll *a* ratio, such as light, nutrient stress, the physiological state of the organisms etc., may, at least in part, be responsible for the observed changes in surface Chl F in the vicinity of fronts, and that the determination of absolute chlorophyll levels may actually reduce, rather than enhance, its potential as a real-time detection method.

SECTION 6.

AN INVESTIGATION OF DIURNAL VARIATION OF THE *IN VIVO* FLUORESCENCE OF CHLOROPHYLL *a*.

6. AN INVESTIGATION OF DIURNAL VARIATION OF THE *IN VIVO* FLUORESCENCE OF CHLOROPHYLL *a*.

6.1. INTRODUCTION

Since chlorophyll fluorescence competes with photosynthesis for energy, it would therefore be expected that chlorophyll fluorescence would show an inverse relationship with the efficiency of photochemical processes. This phenomenon has been reported by several workers (Blasco, 1973; Harris, 1980) in both laboratory and natural phytoplankton populations. A study was therefore undertaken in order to investigate the variation in Chl F over a 24 hour period.

6.2. STUDY AREA

A 24 hour survey was carried out on 19 June 1984 off the edge of the Continental Shelf at Little Sole Bank (47°N, 9°W). The ship's position during the survey period is shown in Figure 46. It can be seen that the ship drifted a considerable distance over the 24 hour period under the combined influence of wind and tidal motion, although it always remained outside the 1000m contour, and should therefore have been well-distanced from the shelf front (Le Févre *et.al.*, 1983).

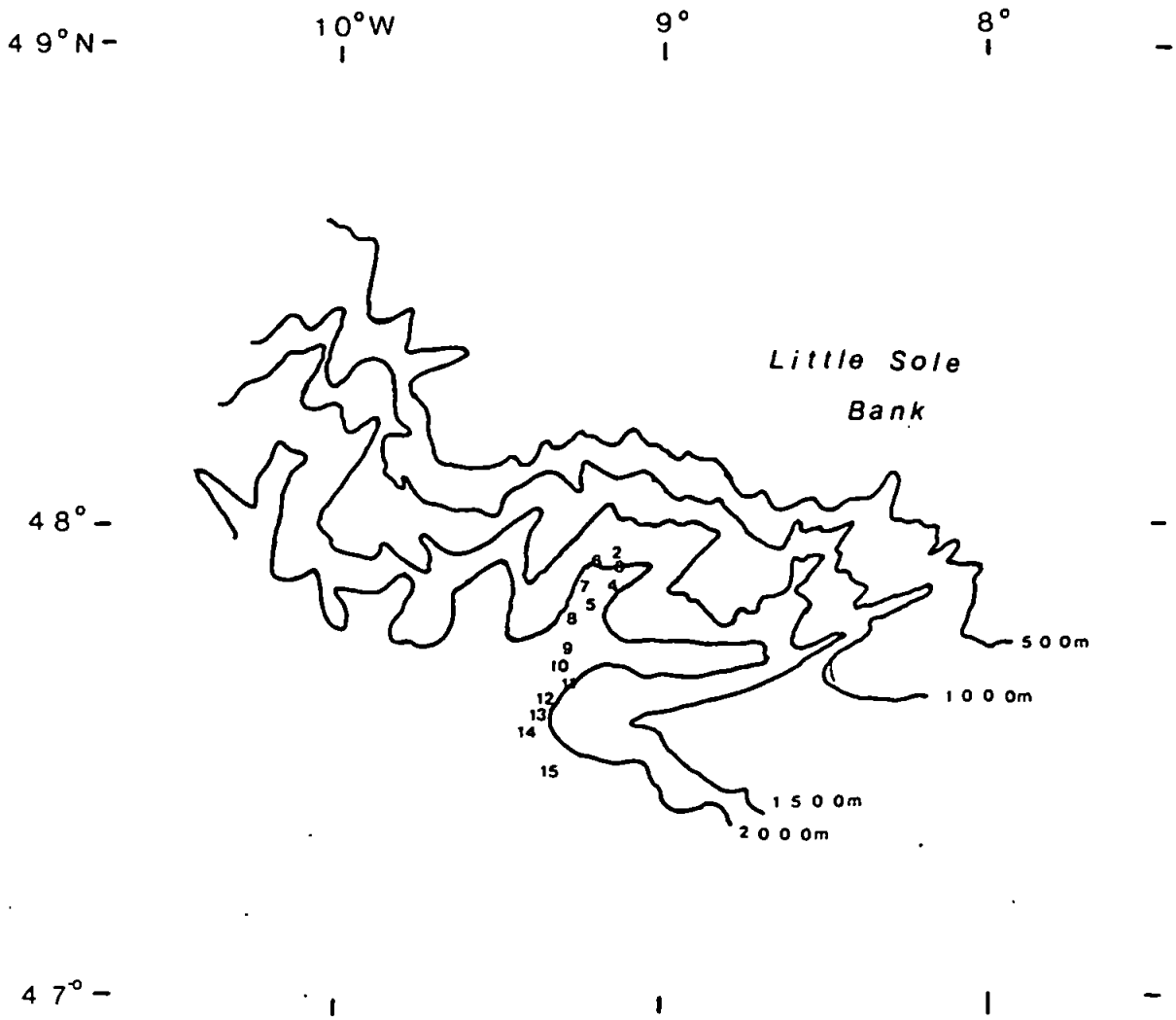


Figure 46. Little Sole Bank, 19-20 June 1984.
Profile Stations 2 to 15.

6.3. RESULTS

6.3.1. Surface Measurements

Chl F at 3m varied from 30 to 180 tus over the survey period (Figure 47) with values increasing sharply from ≈ 60 tus at 1430h to maximum (180 tus) at 1630h, and remaining high (≥150) until 2400h before falling gradually to ≤50 tus at 0600 to 1600h.

Temperature at 3m varied from 15.4 to 17.0°C (Figure 47), increasing gradually from minimum (15.4°C) at 1600h to 15.7°C at 2100h, and remaining relatively constant to 0300h then increasing steadily to maximum (17.0°C) at 1600h.

6.3.2. Depth Measurements:

Temperature & Chlorophyll

The *in vivo* fluorescence of chlorophyll *a* was measured continuously using an ARE Holton Heath multisensor depth profiling system and converted to mg m^{-3} of chlorophyll *a* (Chl F') for comparison with chlorophyll *a* concentrations determined by an *in vitro* spectrophotometric method (Chl S) on discrete samples. The discrete samples were collected on the upcast, at depths determined on the basis of the continuous temperature and chlorophyll fluorescence downcast profiles.

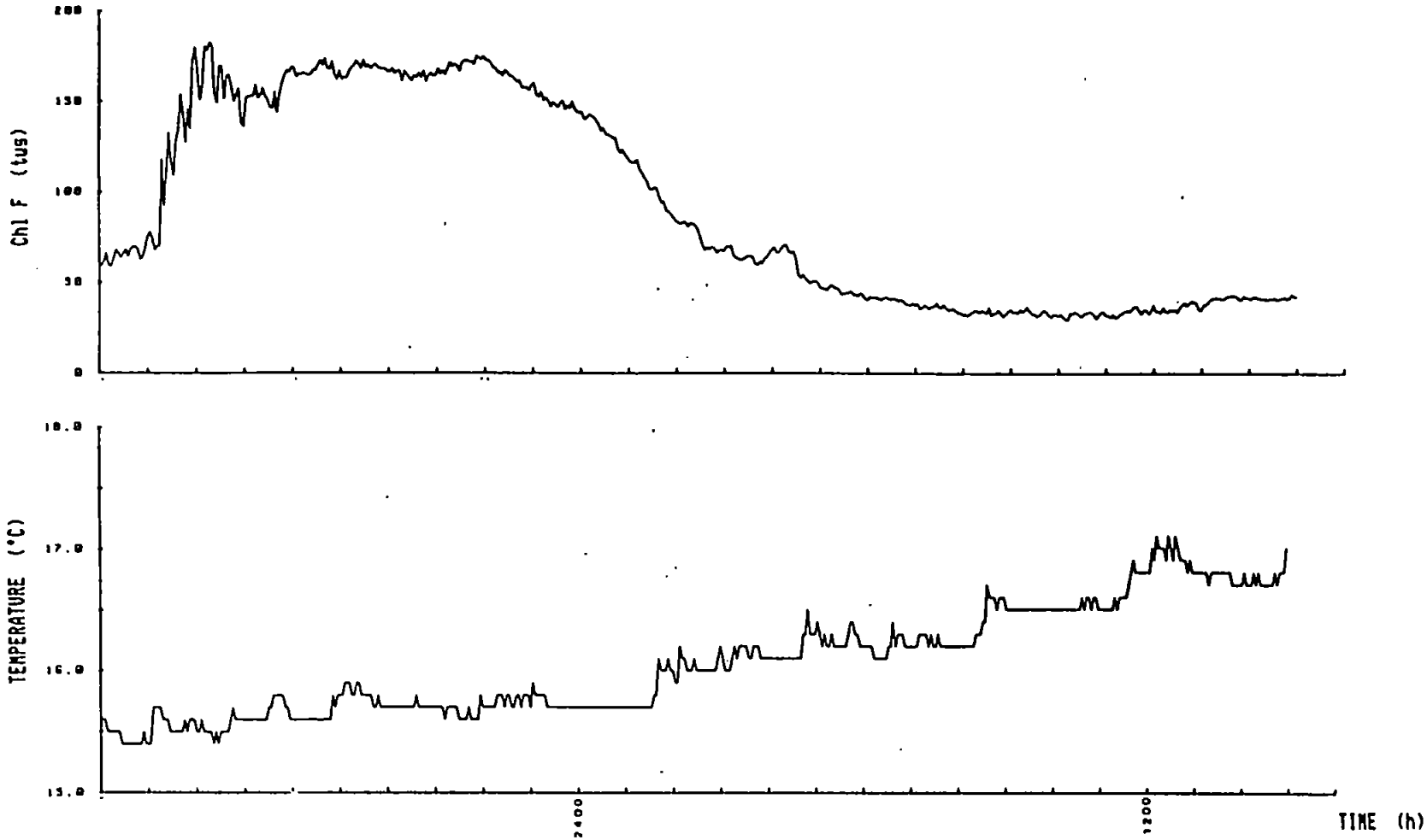


Figure 47. Little Sole Bank, 19-20 June 1984. Distribution of Chl F (tus) and Temperature (°C) at 3m.

Figures 48 & 49 show the large variation in temperature and Chl F' over the survey period.

At station 2 (1450h) temperature varied from 14.2-11.8°C, being isothermal to 20m, with a weak thermocline at 20-28m, and decreasing gradually thereafter to 11.8°C. Chl F' ranged from 0.1-1.26 mg m^{-3}, peaking sharply to maximum at the base of the thermocline (28m) with a large secondary peak at 44m. Chl S ranged from 0.53-1.8 mg m^{-3}, rising from 1.3 mg m^{-3} at 8m to maximum (1.8 mg m^{-3}) at 30m, then falling steadily with depth to minimum (0.54 mg m^{-3}) at 100m. Chl S distribution broadly mirrored Chl F', showing a high positive correlation ($r = +0.9$), but since Chl S was based on discrete, rather than continuous, samples the curve was smoothed.

At 1615h (station 3,) temperature ranged from 14.2 to 11.8°C, falling gradually from maximum at 3m to 13.6°C at 40m, then remaining virtually isothermal to 66m. It then decreased rapidly over the thermocline to 12.7°C at 70m, then gradually to minimum (11.8°C) at 100m. The shape of the Chl F' profile has changed markedly compared with station 2, with the sharp chlorophyll peaks no longer evident. Although the range (0.1-1.4 mg m^{-3}) is only slightly greater than at station 2, there is more Chl F' in the water column, with the bulk of the chlorophyll again above the thermocline, but with the thermocline now much deeper, having been depressed to 66-70m. Chl S

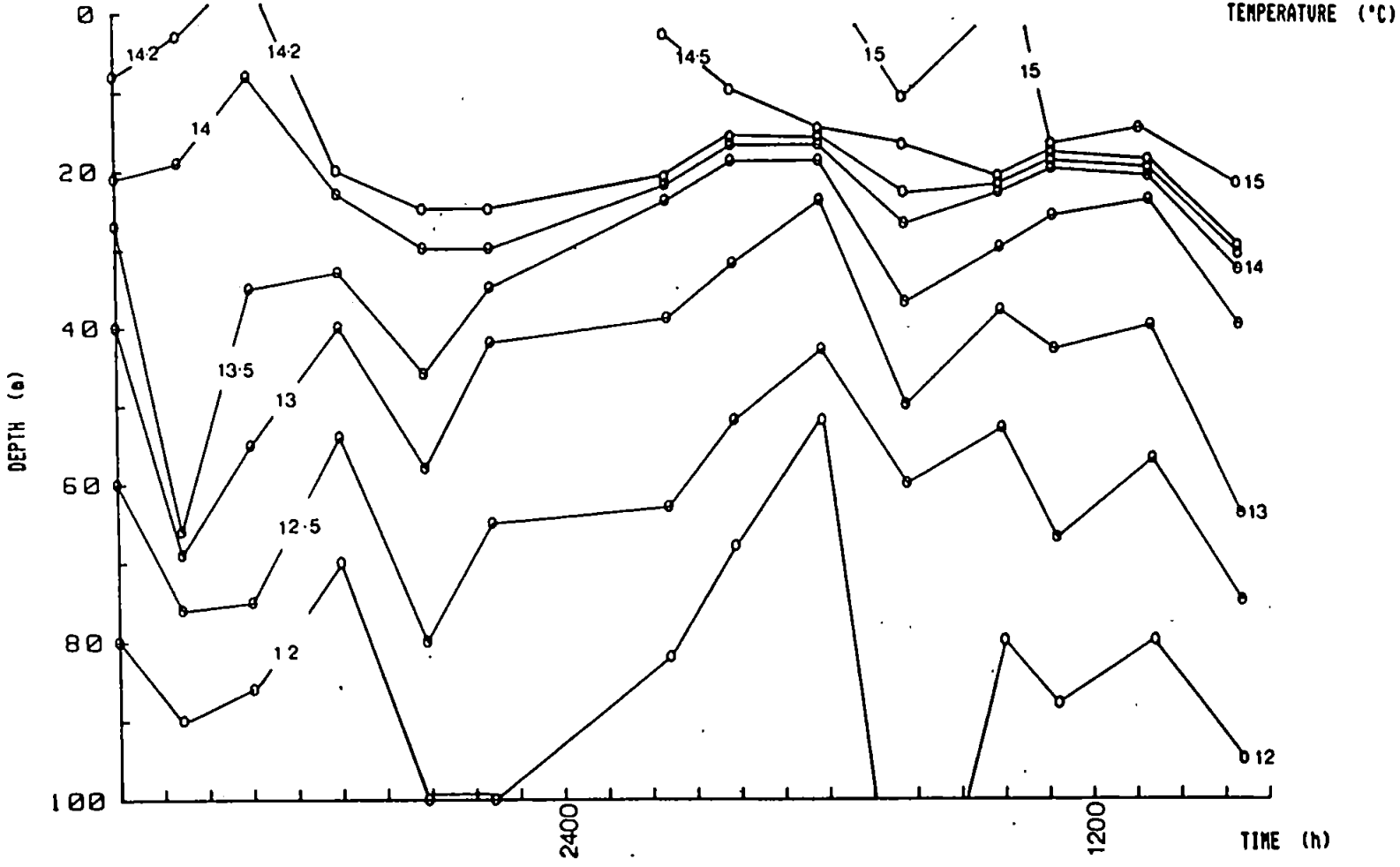


Figure 48. Little Sole Bank, 19-20 June 1984. Distribution of temperature (°C) with depth at Profile Stations (o) 2 to 15.

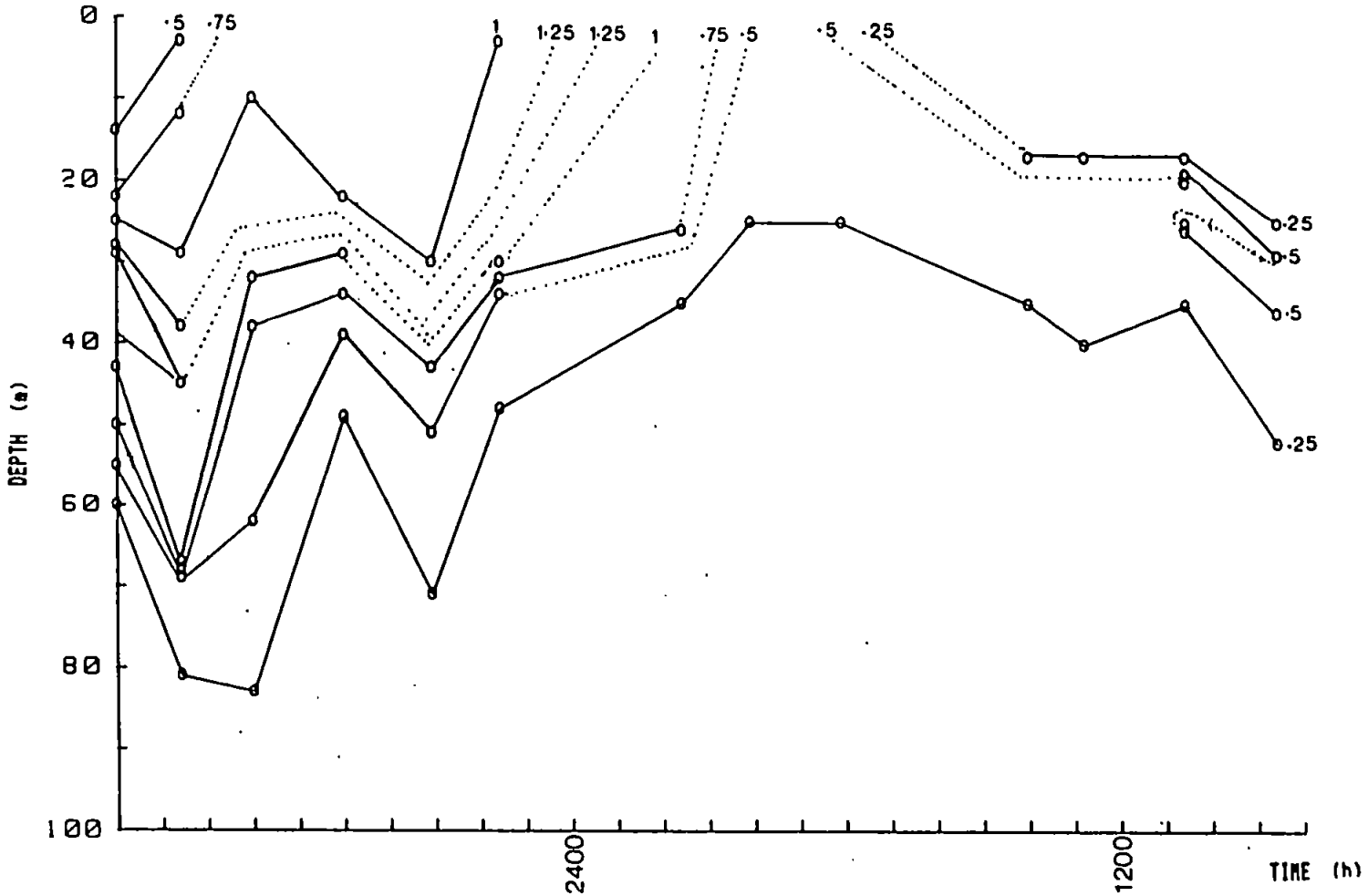


Figure 49. Little Sole Bank, 19-20 June 1984. Distribution of Chl F' (mg m^{-3}) with depth at Profile Stations (o) 2 to 15.

ranged from 0.45 to 1.85 mg m^{-3}, similar to station 2, falling from 1.52 mg m^{-3} at 3m to 0.74 mg m^{-3} at 30m, rising to maximum (1.85 mg m^{-3}) at 60m, then falling steadily with depth to minimum (0.45 mg m^{-3}) at 100m. Chl S shows a negative correlation with Chl F' from 3 - 30m, but a strong positive correlation below 30m, resulting in a drop in the correlation coefficient ($r = +0.7$) over the water column relative to station 2.

At 1750h (station 4) temperature ranged from 14.1 to 11.6°C, the water column appearing to be well-mixed, but with evidence of a weak thermocline (13.8-13.2°C) at 30-40m. SST has dropped by 0.1°C and the temperature at 100m by 0.2°C. Chl F' ranged from 0.08-1.14 mg m^{-3}, giving a high positive correlation with temperature ($r = +0.97$), peaking to maximum (1.14 mg m^{-3}) at 14m and then remaining relatively constant to 30m, dropping fairly rapidly to minimum (0.08 mg m^{-3}) over the very weak thermocline at 30-40m. The bulk of the chlorophyll has now shifted to the top 40m of the water column and, apart from the top 15m, follows the temperature profile. Chl S ranged from 1.01 to 1.92 mg m^{-3}, higher than at station 3, rising sharply from 1.3 mg m^{-3} at 3m to 1.8 mg m^{-3} at 8m, then gradually to maximum (1.92 mg m^{-3}) at 30m before falling gradually to minimum (1.01 mg m^{-3}) at 80m. The correlation between Chl F' and Chl S was slightly higher than at the previous station ($r = +0.8$).

At 1950h (station 5) temperature ranged from 14.2 to 12.0°C, being isothermal to 20m, with a thermocline (14.2-13.0°C) at 20-40m. SST is 0.1°C higher than at station 4, and the 100m temperature showing a significant increase of 0.4°C. The Chl F' pattern is quite different to that at the previous station although the range (0.1-1.15 mg m^{-3}) is similar. The bulk of the chlorophyll is again above 40m, but a sharp peak has developed at 25m in association with the thermocline (20-40m) which now appears to show signs of strengthening. Chl S ranged from 0.76 to 1.43 mg m^{-3}, lower than at the previous stations, rising from 0.97 mg m^{-3} at 3m to maximum (1.43 mg m^{-3}) at 10m, falling slightly to 1.25 mg m^{-3} at 20m, rising again to 1.36 mg m^{-3} at 30m, then dropping steadily to minimum (0.76 mg m^{-3}) at 70m before rising to maximum (1.15 mg m^{-3}) again at 100m.

At 2145h (station 6) temperature ranged from 14.2 to 12.2°C, being isothermal to 20m, and decreasing steadily thereafter, with no well-defined thermocline. SST is the same as at station 5, but the 100m temperature has increased by a further 0.2°C. The amount of chlorophyll in the water column is similar to that at station 5, although the range in values (0.09-0.93 mg m^{-3}) is less, with no sharp peaks. The concentration of chlorophyll is relatively constant at around 0.93 mg m^{-3} (maximum) to 40m, then decreases much more gradually than at station 5 to minimum (0.09 mg m^{-3}) at 100m. Chl S ranged from 0.76 to

1.67 mg m^{-3}, rising from 1.2 mg m^{-3} at 3m to maximum (1.67 mg m^{-3}) at 40m, then falling steadily with depth to minimum (0.76 mg m^{-3}) at 100m. The correlation between Chl F' and Chl S (r) was +0.8.

At 2315h (station 7) SST has increased to 14.3°C and the temperature at 100m has decreased to 12.0°C (0.2°C lower than at station 6). The water column is again isothermal to 22m and the thermocline (14.3-13.2°C) appears to be strengthening between 20m and 40m. The range in Chl F' has increased slightly to 0.09-1.1 mg m^{-3}, due mainly to a change in the vertical distribution, with the chlorophyll now being concentrated in the upper 30m of the water column. Chl S ranged from 0.46 to 1.44 mg m^{-3}, with the bulk of the chlorophyll (>1.0 mg m^{-3}) being above 40m, falling with depth to minimum (0.46mg m^{-3}) at 100m, showing a strong correlation with Chl F' values (r = +0.96).

By 0315h (station 8) SST has increased to 14.5°C and the temperature at 100m has dropped to 11.8°C (0.3°C lower than at station 7), and the thermocline has strengthened at 20-25m (14.4-13.4°C). The amount of Chl F' in the water column is very much less than at the previous stations, ranging from 0.06-0.63 mg m^{-3}, with values above the base of the thermocline (25m) being >0.5 mg m^{-3}, then falling sharply to minimum (0.06 mg m^{-3}) at, and below 50m. Chl S values were also lower (0.34 to 1.25 mg m^{-3}),

rising from 0.97 mg m^{-3} at 3m to maximum (1.25 mg m^{-3}) at 6.6m, then falling steadily with depth to minimum (0.34 mg m^{-3}) at 100m. Chl S again showed a high correlation (r = +0.90) with Chl F'.

At 0445h (station 9) temperature varied from 14.5 to 11.6°C, with the thermocline gradient further strengthened at 15-20m, shallower than at station 8, and decreasing gradually thereafter. SST was the same as at station 8, but the downward trend in the 100m temperature was observed to be continuing. The total Chl F' in the water column has decreased further, ranging from 0.06-0.42 mg m^{-3}, with maximum values just above the thermocline at 15-20m - shallower than at the previous stations. Chl S ranged from 0.33 to 0.9 mg m^{-3}, lower than at station 8, falling steadily from maximum (0.9 mg m^{-3}) at 3m to minimum (0.33 mg m^{-3}) at 100m. Chl S again showed a high positive correlation (r= +0.98) with Chl F'.

At 0645h (station 10) temperature varied from 14.6 to 11.7°C, with a strong thermocline (14.6-13.4°C) at 15-20m, then decreasing in "steps" to 50m, and gradually thereafter. SST had increased further, and was 0.4°C higher than at station 7. The total Chl F' in the water column has fallen further, with values ranging from 0.05-0.36 mg m^{-3}. The vertical distribution of Chl F' was similar to that at station 9, but with a slight peak evident at the base of the thermocline at 20m. Chl S

ranged from 0.22 to 0.76 mg m^{-3}, rising from 0.59 mg m^{-3} at 3m to maximum (0.76 mg m^{-3}) at 15m, then falling to minimum (0.22 mg m^{-3}) at 50m before increasing slightly to 0.39 mg m^{-3} at 68.5m and decreasing again to 0.28 mg m^{-3} at 100m. Chl S again showed a high positive correlation with Chl F' (r= +0.90)

By 0830h (station 11) the temperature profile has changed dramatically. SST has increased to 15°C with only minor solar radiation, and the 100m temperature shows a very significant increase to 12.2°C. The water column is isothermal to 11m and the thermocline (15.0-14.0°C) has become shallower (11-17m), with a further gradual temperature gradient (14.0-12.5°C) from 17-60m. Unfortunately, no data are available for Chl F' at station 11 due to instrument failure. Chl S ranged from 0.34 to 0.87 mg m^{-3}, rising from 0.59 mg m^{-3} at 3m to 0.87 mg m^{-3} (maximum) at 11m, then falling steadily to minimum (0.34 mg m^{-3}) at 100m.

At 1050h (station 12) the temperature profile (14.9-11.9°C) had again changed markedly, with SST being 0.1°C lower than at station 11 and a much more significant decrease of 0.3°C at 100m, with the water column being isothermal to 15m. The thermocline gradient was again strengthened (14.9-13.5°C) at 15 to 26m, and there is evidence of a slight temperature inversion at 28m. Chl F' ranged from 0.05-0.37 mg m^{-3}, as at station 10, but the

distribution is quite different, rising from 0.15 mg m^{-3} at 3m and 10m to maximum at 28m, coincident with the temperature inversion at the base of the thermocline. Chl S ranged from 0.16 to 1.22 mg m^{-3}, higher than at station 11, rising from minimum (0.16 mg m^{-3}) at 3m to maximum (1.22 mg m^{-3}) at 26m, then falling again to minimum at 100m. The correlation between Chl S and Chl F' at station 12 had dropped to +0.7.

At 1215h (station 13) temperature ranged from 15.0 to 11.8°C, being isothermal to 15m, with a thermocline (15.0-13.2°C) at 15-30m. The temperature inversion evident at station 12 has disappeared, and SST has increased, being 0.8°C higher than at station 7 (where SST first started to increase), with the temperature at 100m dropping to 11.8°C. Chl F' ranged from 0:06-0.37 mg m^{-3}, with low levels (0.13-0.16 mg m^{-3}) to 10m, then increasing to maximum (0.37 mg m^{-3}) at 20m before falling gradually to minimum (0.06 mg m^{-3}) at 100m, the bulk of the chlorophyll being slightly shallower than at the previous station. No discrete samples were obtained at this station due to failure of the sampling rosette.

At 1415h (station 14) SST has increased further to 15.2°C, possibly as a result of solar radiation, although the 100m temperature, which would not be affected by this has also increased by 0.15°C to 11.9°C. The water column is again isothermal to 15m, similar to stations 12 and 13,

but the thermocline gradient (at 15-20m) is very much sharper (15.2-13.5°C). Chl F' levels have increased (0.05-0.93 mg m^{-3}), rising from 0.13 mg m^{-3} at 3m to 0.93 mg m^{-3} (maximum) at the base of the thermocline (21m), then falling to 0.32 mg m^{-3} at 30m, and gradually thereafter to minimum (0.05 mg m^{-3}) at 100m. Chl S ranged from 0.39 to 1.96 mg m^{-3}, peaking at 40m, then falling to minimum (0.39 mg m^{-3}) at 100m. There was no correlation between Chl F' and Chl S (r= +0.06).

At 1650h (station 15) the temperature range over the water column was the same as at station 14 (15.2-11.9°C), but the profile is markedly different, being isothermal to 20m with a very diffuse thermocline at 20-40m (15.2-13.5°C). Temperatures from 20 to 80m were all higher than those recorded at station 14 for the same depths. The range in Chl F' (0.05-0.55 mg m^{-3}) is less than at the previous station, although the total Chl F' over the water column remains similar. The sharp peak at 21m is no longer evident, although there is still an increase in Chl F' associated with the thermocline at 26-40m. Chl S ranged from 0.27 to 0.89 mg m^{-3}, falling from 0.64 mg m^{-3} at 3m to 0.46 mg m^{-3} at 10m, then rising to 0.89 mg m^{-3} (maximum) at 26-35m and falling to minimum (0.27 mg m^{-3}) at 100m. The correlation between Chl S and Chl F' (r) rose again to +0.75.

ATP, Chl S and Nutrients

The distribution of log ATP, Chl S, phosphate, nitrate and silicate in the top 100m of the water column are shown in Appendix 3.

Log ATP showed no apparent differences between the two water masses. The distribution of Chl S was similar to that of Chl F'.

All three nutrients were generally low at stations 2 to 6, with concentrations increasing at stations 7 to 15.

6.4. DISCUSSION

The distribution of Chl F' with depth over the survey period (Figure 49) was broadly similar to that of chlorophyll determined spectrophotometrically (Chl S, Appendix 3). It was expected that the relationship between Chl F' and Chl S over the 24 hour survey period would be consistent with the results obtained by other workers (Karabashev & Solov'yev, 1976; Owens *et.al.*, 1980), with the highest correlation between Chl F and Chl S being found at midnight, and the lowest at noon.

However, although high positive correlations ($r>+0.9$) were found between Chl F and Chl S at stations 7 to 9 (2315 to 0645h), the highest correlation occurred not at

2400h, but at 0445h (station 9), and the lowest (r=+0.05) at 1415h on 20 June (station 14).

If *in vivo* chlorophyll fluorescence was exhibiting a periodicity (even if out of phase with that reported in the literature), then the correlations between Chl F' and Chl S at the same times of day should have been similar. This was not the case, however. At 1450h on 19 June (station 2) the correlation was high (r=+0.90), but at 1415h 20 June (station 14) the correlation was very low (r=+0.05). Diel periodicity was not, therefore, the major factor influencing the *in vivo* fluorescence yield.

The changes in the depth of the isotherms (Figure 48) show a similar pattern to the distribution of Chl F', suggesting that the changes in Chl F over the survey period are strongly related to changes in the temperature structure of the water column which are masking any diurnal variation in fluorescence.

Evidence of internal wave motion can be clearly seen in Figure 48, with the depth of the isotherms varying markedly between profiles. A regular pattern cannot be discerned owing to the temporal spacing of the profiles, which was not short enough to detect the periods of the internal waves. A particularly interesting feature evident in Figure 48 is the strenghtening of the thermocline and the rise in surface temperature from station 7 (2315h) to the end of the survey period at 1630 Hrs. The development of the thermocline is associated

with a fall in the chlorophyll content of the water column, with the highest chlorophyll values occuring prior to, and coincident with the strengthening thermocline from 1430h to 2315h. Higher rates of fluorescence would, of course, be expected during the night, when no photosynthesis is taking place. However, Chl S values are also higher before 2315h, indicating that the variation in chlorophyll determined by fluorometric methods is real, and not an effect produced exclusively by diel periodicity fluorescence levels.

Continuous measurements of Chl F and temperature at 3m are shown in Figure 47. There is a dramatic fall in chlorophyll levels prior to an increase in surface temperature of approximately 1°C (0200h), indicating either a change in water mass, or a previous period of upwelling which has resulted in an increase in phytoplankton productivity due to increased availability of nutrients.

The ship's position during the survey period is shown in Figure 46. It can be seen that the ship drifted a considerable distance over the 25-hour period as a result of wind and tidal motion, although it always remained outside the 1000m contour and should therefore have been well-distanced from the shelf front. The drift was predominantly due to the effects of wind, since there is no evidence of the cyclic pattern which would have been expected had tidal motion been the dominant factor.

The profile stations appear to be in two groups, roughly corresponding to the mixed and stratified areas evident in Figure 47, supporting the hypothesis that the measurements were taken in two distinct water masses - one strongly stratified, and the other an area where upwelling prior to the survey period has modified the water column. This factor, combined with the internal wave motion, appears to have masked any effect of diurnal variation on chlorophyll a fluorescence emission.

One particularly interesting interesting feature to emerge is the sharp increase in Chl F at 3m seen at the beginning of the survey period (Figure 47, 1200-1400h) which should indicate the proximity of a second front.

This suggests that the vertical profiles were taken at the Celtic Sea - Bay of Biscay shelf break front, an area of relatively low surface temperature which is limited by a double frontal system (Le Févre *et.al.*, 1983).

Very little is so far known about this double frontal system. Pingree *et.al.* (1981) have reported high surface chlorophyll and nutrient concentrations at the shelf break, although the present study indicates nutrient depletion in the mixed water as a result of high phytoplankton productivity.

This area was thought to be the result of upwelling at the shelf edge (Dickson *et.al.*, 1980; Heaps, 1980). However, Mazé (1980, 1983) postulated that the surface cooling was a result of processes depending on the generation of internal waves over the slope, and modelled a simulated propagation of the barotropic tidal wave towards the shelf. The result was the generation of internal waves over the shelf break, with a maximum amplitude of 50-60m, resulting in an outcropping of the thermocline at the surface.

SECTION 7

7. CONCLUSIONS

7. CONCLUSIONS

1) This study has shown that the real-time monitoring of chlorophyll *a* fluorescence (Chl F) can be used to detect the surface position of a deep-sea front (Section 3), a shelf-sea front (Sections 4 & 5), and a shelf-break front (Section 6).

The seasonal surface monitoring programme carried out around the UK (Section 4) indicated that when stratification was at its most pronounced, (June to September), changes in Chl F were consistently associated with temperature and salinity gradients at the shelf sea fronts around the UK. These changes in Chl F were not, however, necessarily co-incident with the temperature and salinity gradients, but often appeared to precede both the temperature and salinity response.

It was expected that during the winter months (November and December), when the water column was well-mixed, Chl F values would be uniformly low, reflecting low phytoplankton productivity, and giving a relatively stable base line around the UK. This was found to be the case, with Chl F ranging from 0.5-13 tus and chlorophyll *a* from 0.0-1.5 mg m^{-3}.

However, even at these low levels, Chl F showed similar variations to those seen from June to September. These changes in Chl F were, however, apparently associated more with changes in salinity than with changes in temperature, as the temperature differentials during the winter months were slight.

These results indicate that the changes in chlorophyll levels found in the vicinity of shelf sea fronts during the summer months are likely to be consistent features (not transient, as suggested by Savidge, 1976), which are also associated with temperature and salinity gradients at other times of the year - a finding which has important implications for ASW.

2) The results of the surface monitoring programme across the Ushant front in June 1984 showed that at a rate of change of 10.0% (C1), Chl F detected 100% of all crossings and skirtings, 78% of the detections being in advance of T1 (by 0.5 to 2.0 miles), with no false alarms.

When the sensitivity was raised to a rate of change of 5.0% (C2) all crossings and skirtings were again detected, with 76% of the alarms being raised in advance of T1 and the distance advantage increasing to 0.5 to 5.0 miles.

The fall in the percentage of alarms flagged before T1 was due to an increase in the false alarm rate to 14%. If the number of false alarms was disregarded, however, the percentage of flags raised in advance of T1 rose to 89%.

A difficulty in classifying alarms as "real" or "false" arose from the fact that both C1 and C2 flagged alarms in areas where T1 did not detect any major temperature change. However, on the majority of occasions when this occured, the Chl F alarms were associated with very slight temperature changes. These flags may therefore not in fact be "false" alarms, but an indication of the proximity of a front which has not, as yet, been detected by temperature. This would appear to be a likely interpretation, since the results for C1 indicate a high percentage (78%) of detections occuring in advance of temperature. The 'true' false alarm rate for Chl F could therefore be much lower than that quoted in the text.

3) The study of the Ushant front (Section 5) showed that Chl F' maxima were often, though not always, associated with the thermocline, in contrast with the results of Pingree *et.al.*, (1976) and Aiken & Taylor (1984), who have reported chlorophyll thermocline maxima over the whole stratified area of the continental shelf.

However, Chl F' maxima were occasionally also found in the mixed water at around the same depth as the thermocline of the stratified water.

Chl F' showed no correlation at any depth with either water mass, or with the frontal region.

The lack of correlation between Chl F' and specific water masses is not, perhaps, surprising, since this was also found to be the case in the surface monitoring programme, where it was the *rates of change* in Chl F in the vicinity of the front which were found to be critical, rather than absolute levels.

Although the results of this study give no firm indication that Chl F' can be used as a means of detecting the subsurface position of a front, the possibility cannot be ruled out. The rapid advection of the two water masses on the East/West transect 5 (Section 5) illustrate that insufficient depth profile data were collected to estimate the rates of change in Chl F' between profile stations.

Such a calculation would require continuous fluorescence measurements over the water column across the front. One possible method for making measurements of this sort may be the use of an undulating oceanographic recorder (Aiken & Taylor, 1984), although this also poses

problems due to the way the instrument samples over the water column.

4) The surface monitoring programmes (Sections 4 & 5) indicated that changes in pH also occured in the vicinity of shelf-sea fronts, suggesting that the real-time monitoring of pH might offer some potential as an advance warning technique. However, such variations in pH were not found to be consistent features of the frontal systems, but appeared to be local peturbations, possibly brought about as a consequence of biological activity.

5) The results of the surface monitoring programme across the Ushant front (Section 5) showed that at a rate of change of 0.4% (pH1), pH detected 63% of the crossings and 30% of the skirtings, the false alarm rate being 33%, with 25% of the detections occurring 0.5 to 1.5 miles in advance of T1.

pH2 (0.3%) detected 75% of crossings and 40% of skirtings, with a false alarm rate of 33%. The percentage

of alarms raised in advance of T1 rose slightly to 27%, and the distance advantage increased to 0.5 to 2.0 miles.

Increasing the sensitivity of this parameter by lowering the rate of change below 0.3% did not improve the percentage of detections, but merely resulted in an increase in the false alarm rate.

pH1 and pH2 flagged far fewer alarms in advance of T1, with a much higher false alarm rate, than did C1 and C2. Also, if the sensitivity of the rate of change in pH was raised beyond 0.3%, alarms were flagged in what appeared to be a random pattern, bearing little relation to either large or small variations in temperature. On these grounds, therefore, the argument that some of the alarms designated as false are actually indications of the proximity of another water mass, would not appear to be as strong for pH as for Chl F.

6) Although the surface monitoring programme indicated some potential as an advance warning technique, pH measurements showed no correlation with either mixed or stratified water at any depth throughout the water column. It is therefore considered unlikely that any advantage would be gained by using pH (in preference to Chl F) to detect either surface, or subsurface, fronts.

7) No correlation was found at any depth between ATP and either mixed or stratified water masses, or the frontal region (Section 5).

It is, of course, possible that the same arguments which have been applied to Chl F' distribution (where it is the *rate of change* which is critical, rather than the absolute concentration) may also apply to ATP. However, since insufficient depth profile data were collected to estimate the rates of change in ATP concentration between profile stations, and continuous monitoring techniques already exist for chlorophyll fluorescence, but not for ATP estimations, it is unlikely that the development of this method as a real-time detection method would prove more profitable than the use of Chl F', or of Chl F.

8). Estimates of particle size counts across the front were found to be unpracticable due to difficulties in leveling the mercury in the Coulter Counter manometer at sea. It was considered that this problem could not be overcome by the use of a gimbal mounting.

9) In contrast to the findings of Slovacek & Hannan (1977), the results of the present study (Section 5) indicate that, in natural marine phytoplankton populations, DCMU addition does not give maximal *in vivo* fluorescence yields which are a constant function of cellular chlorophyll *a*.

Although F+DCMU was enhanced in the majority of samples, F+DCMU did not always show a better correlation with Chl S than did F-DCMU, and in some cases, the correlation between fluorescence and Chl S was actually reduced. The degree of correlation between F+DCMU and Chl S did not appear to be a function of temperature, nutrient status or of the light/dark cycle. In addition, the distribution of F+DCMU throughout the water column showed no correlation with either the mixed or stratified water across the front. It would not appear, therefore, that the addition of DCMU would give a more accurate estimation of Chl S, nor is the addition of DCMU by continuous injection techniques likely to improve the degree of advance warning given by Chl F on approaching a front.

10) The possibility must be considered that the very factors which affect the fluorescence:chlorophyll *a* ratio, such as light, nutrient stress, the physiological state of

the organisms etc., may, at least in part, be responsible for the observed changes in surface Chl F in the vicinity of fronts, and that the determination of absolute chlorophyll levels may actually reduce rather than enhance its potential as a real-time detection method.

11) Traditional sampling methods, such as the use of Nansen bottles or pumps in collecting samples for pigment analysis, imply some sort of steady state over the water column. However, although very little is known of the effects of internal waves propagating on-shelf from the shelf-break, Aiken & Taylor (1984) have shown that, in the English Channel, internal wave action can move the chlorophyll maximum over a distance of 10m with a period of about 10 minutes.

Internal wave activity therefore poses methodological problems in sampling procedures, and may therefore have been a contributary factor to the variation in the correlation found between Chl F and Chl S in the present study, where fluorescence was measured on the downcast (≈ 10 minutes) and samples taken for pigment analysis on the upcast (≈ 20 minutes).

12) Internal wave activity, combined with a change in water mass, was responsible for masking any variation in *in vivo* chlorophyll fluorescence yield during the 24 hour survey carried out at Little Sole Bank (Section 6).

It was expected that the relationship between Chl F and Chl S over the 24 hour survey period would be consistent with the results obtained by other workers (Karabashev & Solov'yev, 1976; Owens *et.al.*, 1980), with the highest correlation between Chl F and Chl S being found at midnight, and the lowest at noon. This was not the case, however.

If *in vivo* chlorophyll fluorescence was exhibiting a periodicity (even if out of phase with that reported in the literature), then the correlations between Chl F and Chl S at the same times of day should have been similar. However, this was not found to be the case. Diel periodicity was not, therefore, the major factor influencing the *in vivo* fluorescence yield.

The changes in the depth of the isotherms showed a similar pattern to the distribution of Chl F', suggesting that the changes in Chl F over the survey period were strongly related to changes in the temperature structure of the water column which were masking any diurnal variation in fluorescence.

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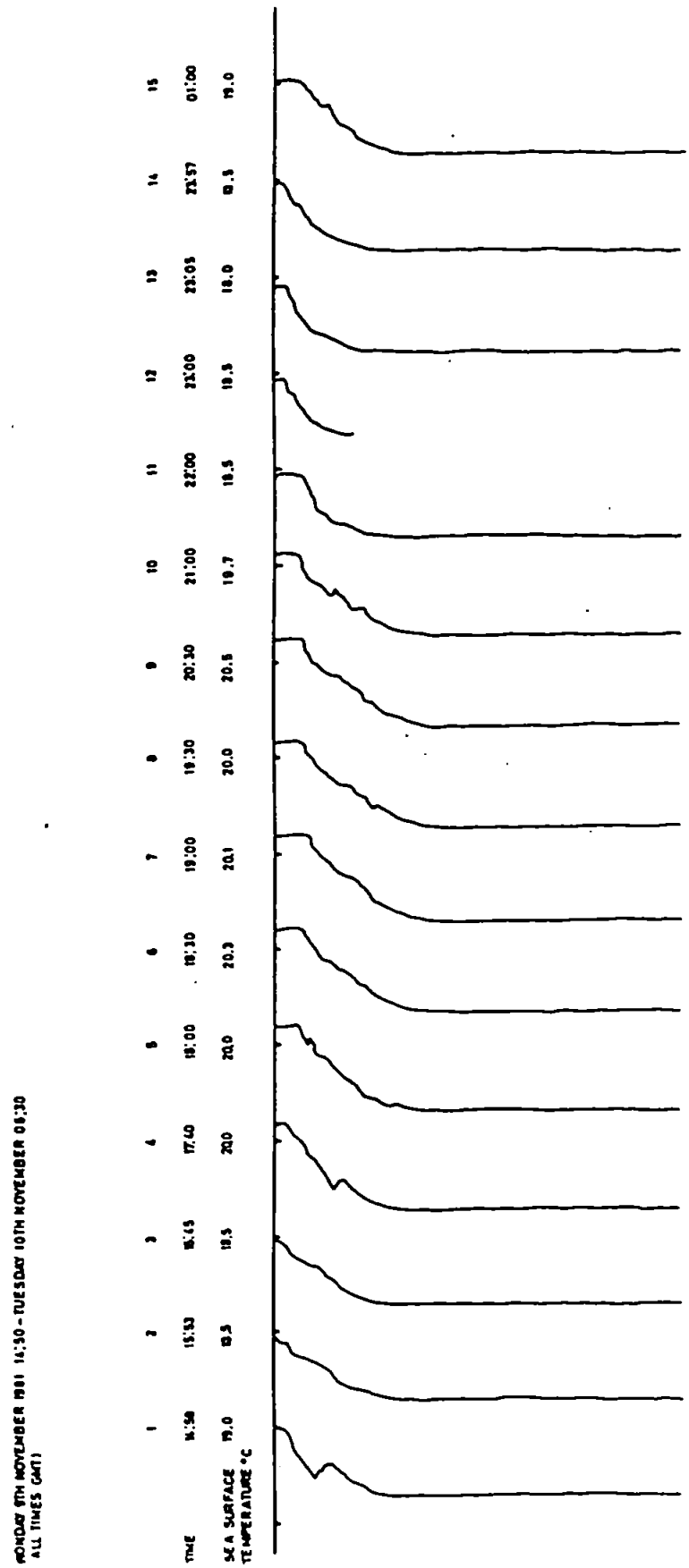
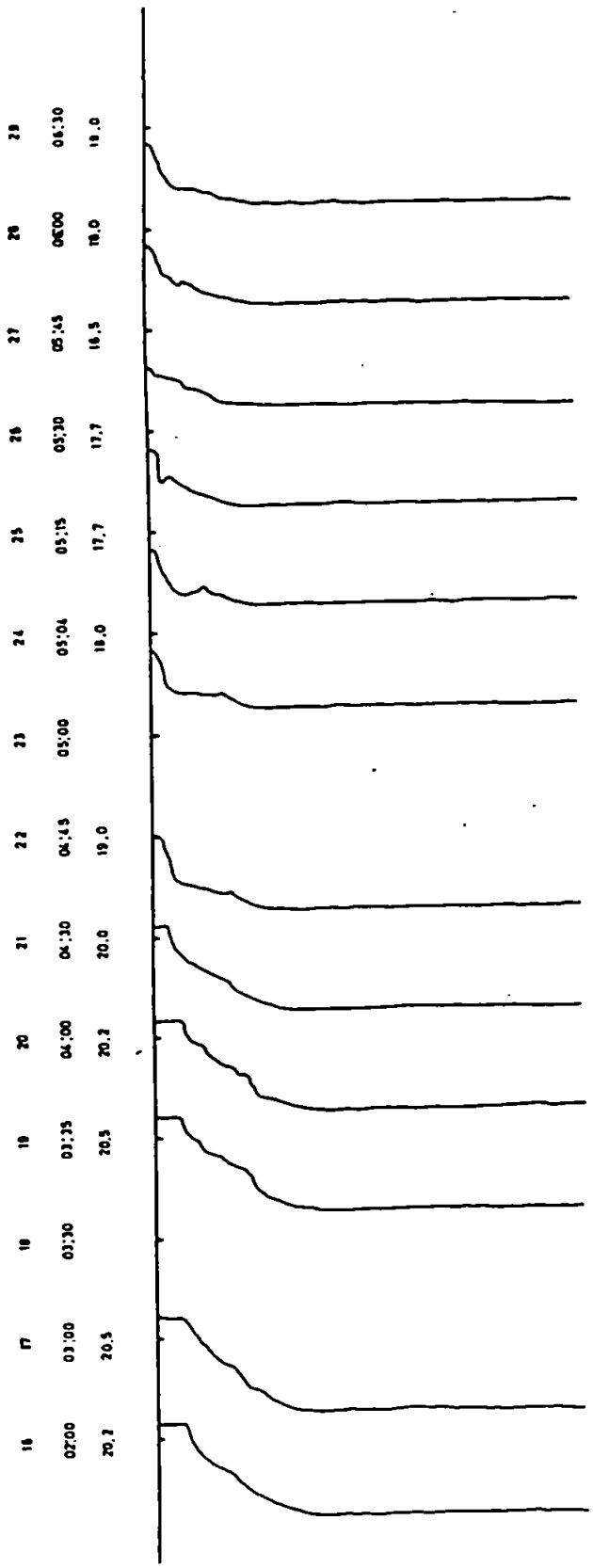
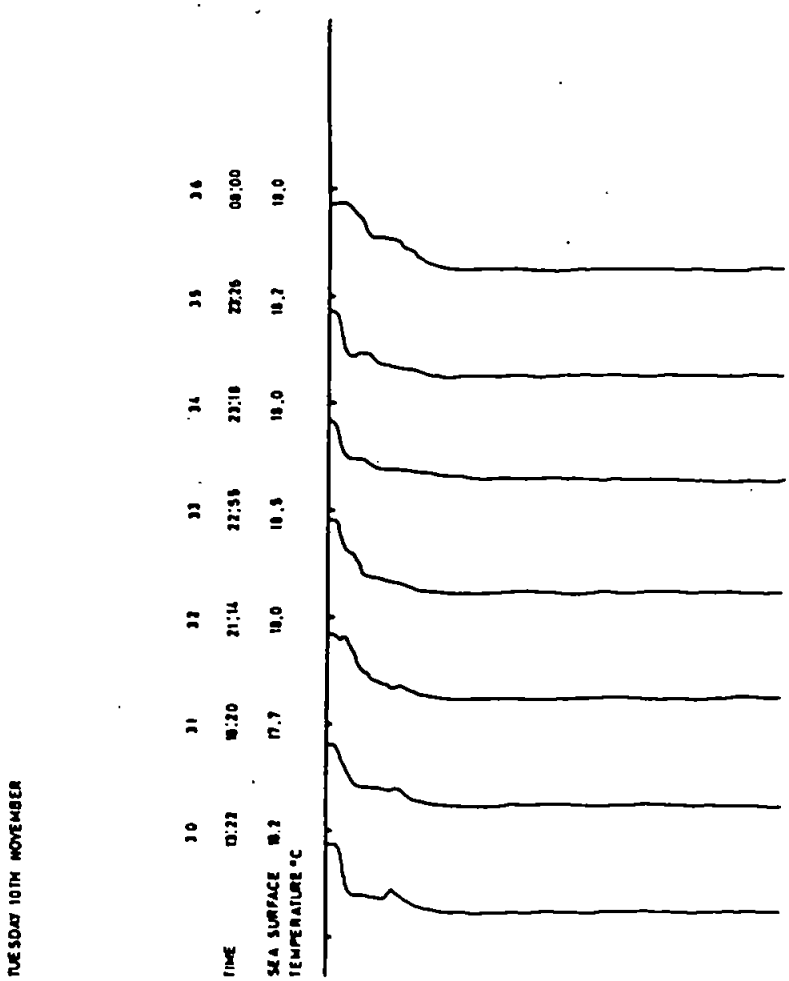
APPENDIX 1

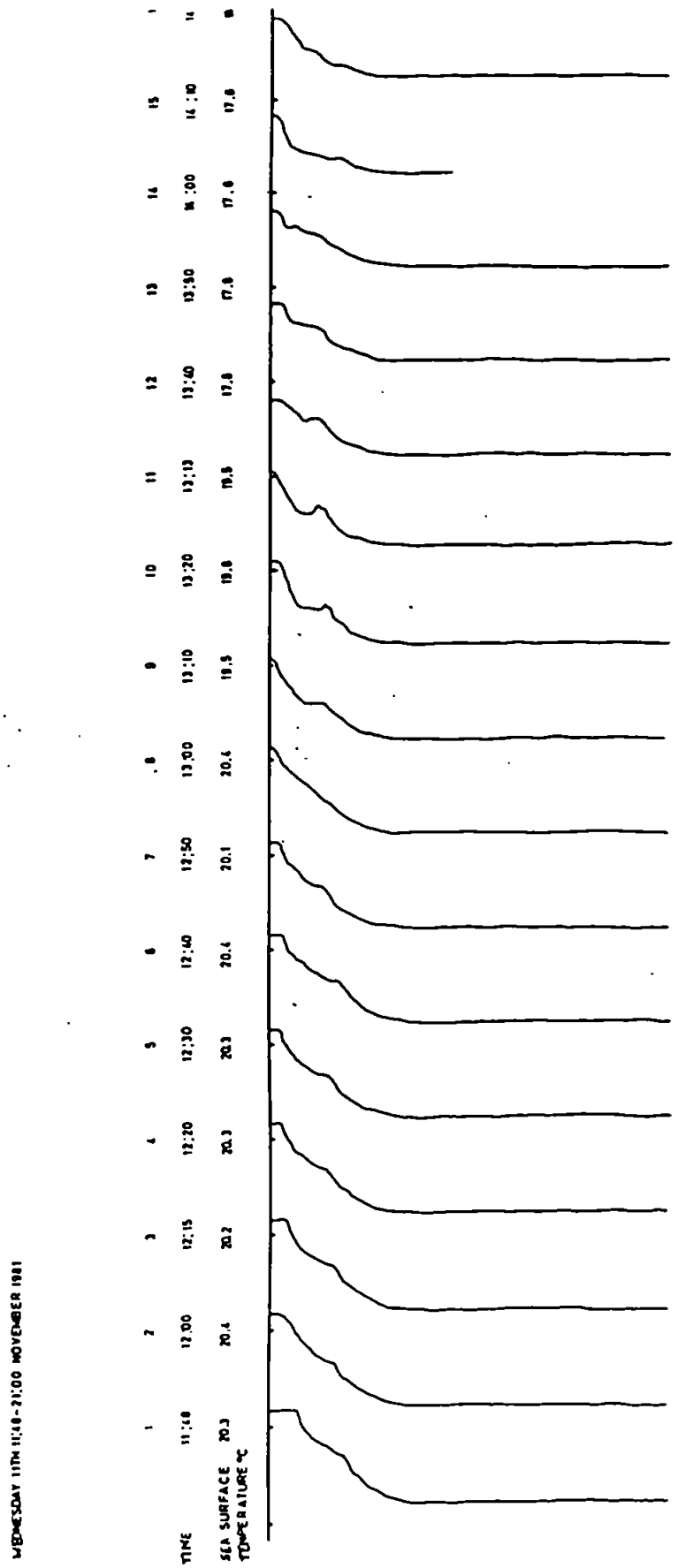
XBT data for the Alboran Basin, 9-12 November 1981.


MONDAY 9TH NOVEMBER 1981 14:30 - TUESDAY 10TH NOVEMBER 05:30
ALL TIMES (GMT)
TIME
SEA SURFACE TEMPERATURE °C
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
14:30 15:30 16:15 17:40 18:00 18:30 19:00 19:30 20:30 21:00 22:00 23:00 23:05 23:57 01:00
19.0 18.5 18.5 20.0 20.0 20.3 20.1 20.0 20.5 19.7 18.5 18.5 18.0 18.5 19.0

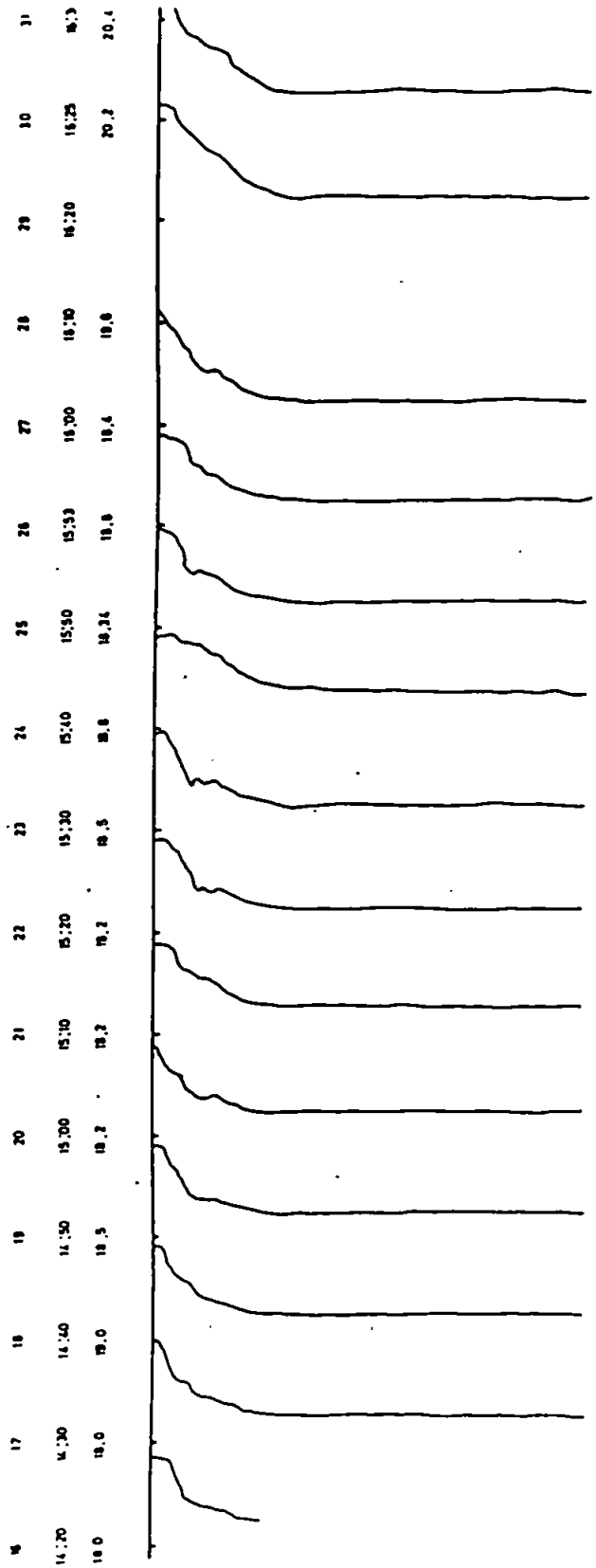
APPENDIX 1. (continued)



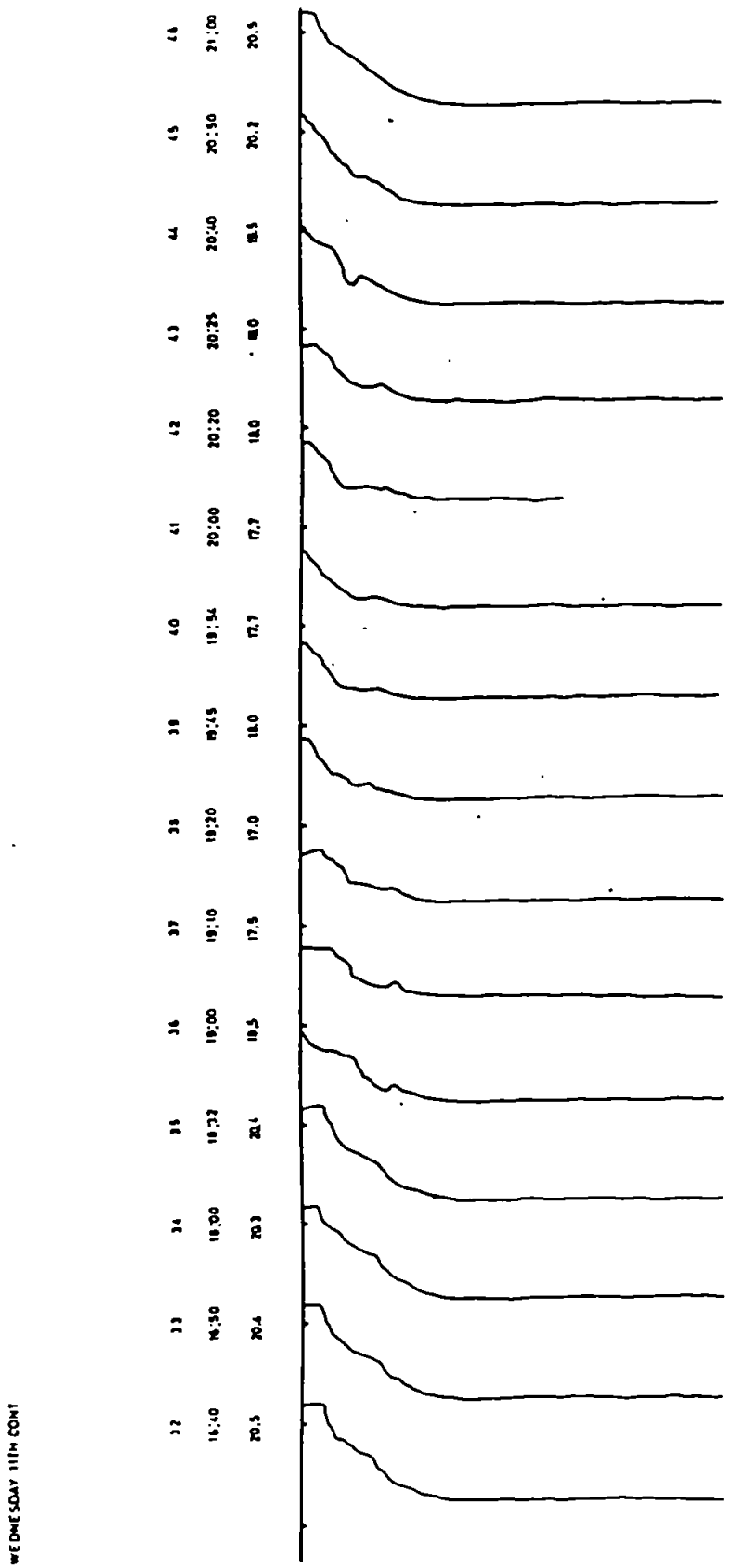

TUESDAY 10TH NOVEMBER
TIME
SEA SURFACE TEMPERATURE °C
10
13:22
8.2
11
10:20
17.7
12
21:14
18.0
13
22:58
18.5
14
23:18
18.0
15
22:36
18.2
16
08:00
18.0


WEDNESDAY 11TH 11:40-21:00 NOVEMBER 1981
TIME
SEA SURFACE TEMPERATURE °C

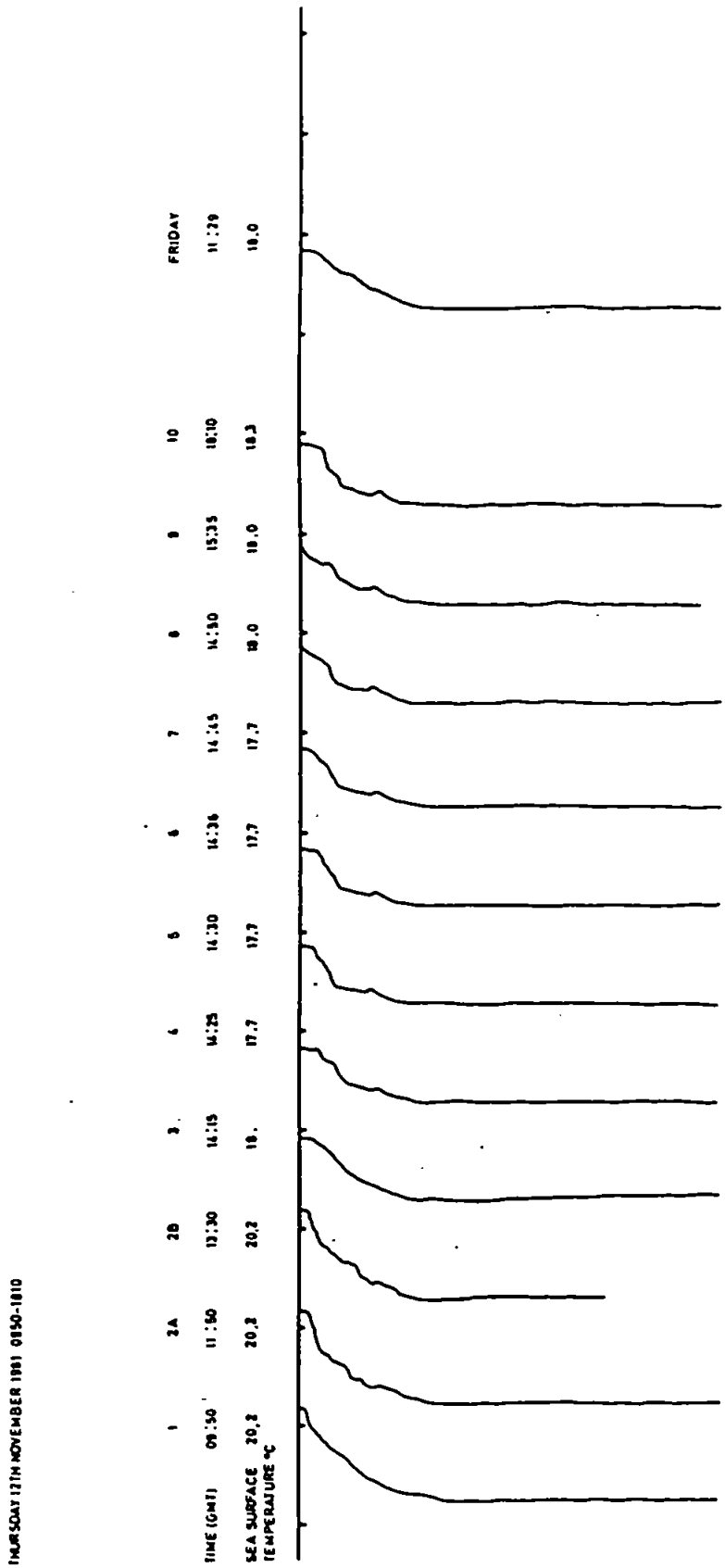
APPENDIX 1. (continued)



APPENDIX 1. (continued)



WEDNESDAY 11TH CONT


THURSDAY 12TH NOVEMBER 1981 0150-1810
TIME (GMT)
SEA SURFACE TEMPERATURE °C
FRIDAY

APPENDIX 2

APPENDIX 2

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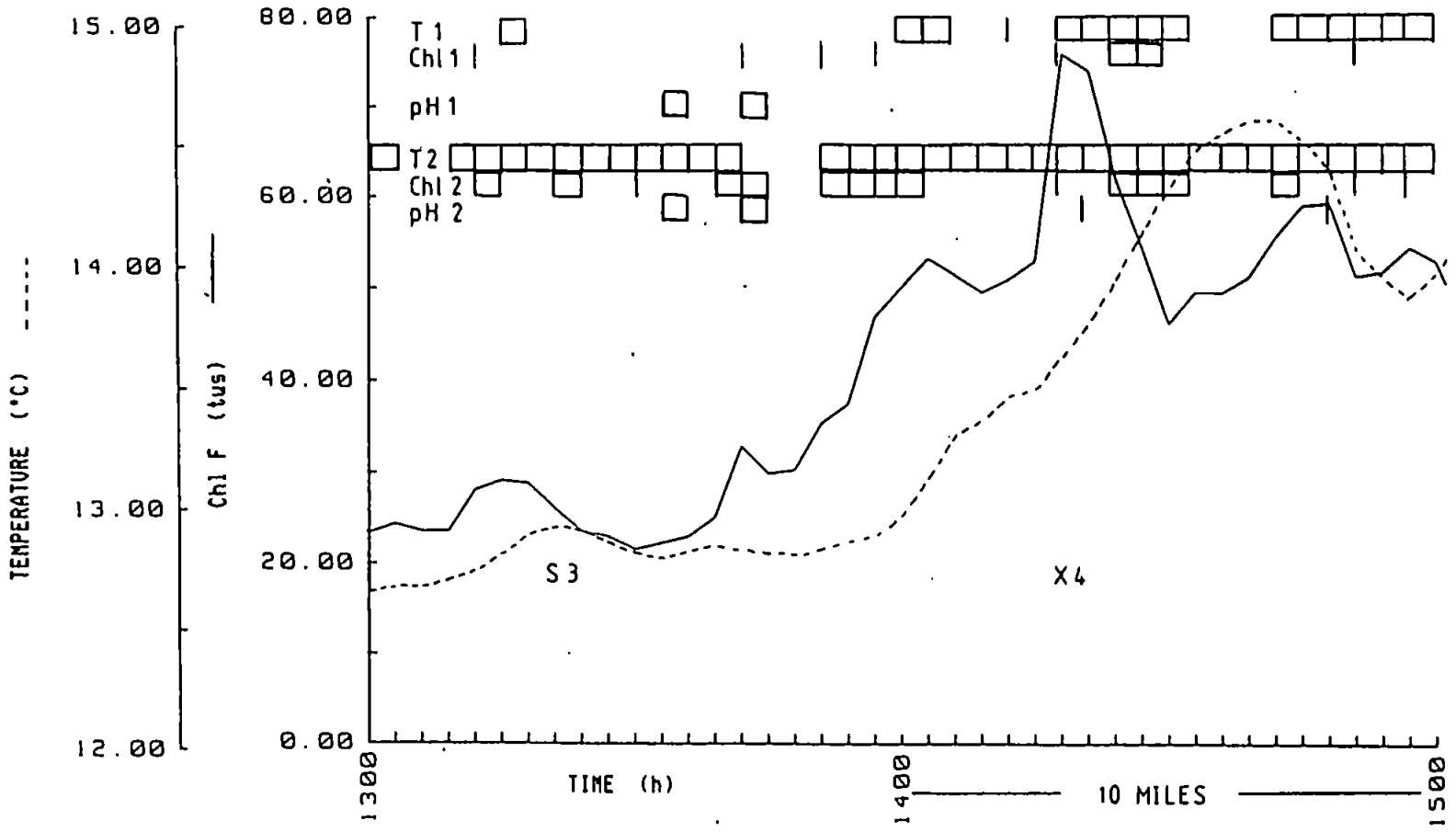


Figure 2.1.1. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) at skirting S3 and crossing X4 of the Ushant front, 13 June 1984.

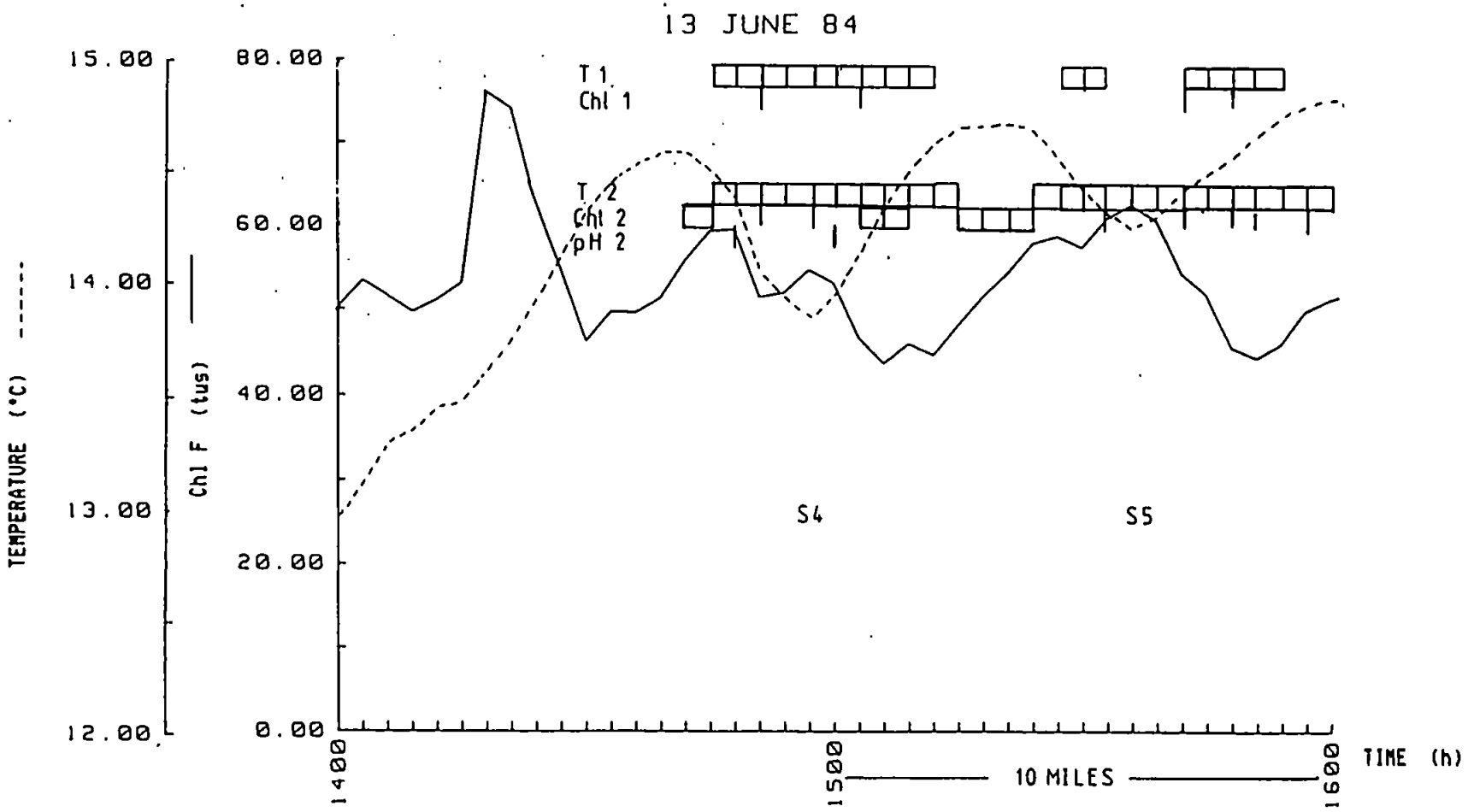


Figure 2.1.2. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) at skirtings S4 and S5 of the Ushant front, 13 June 1984.

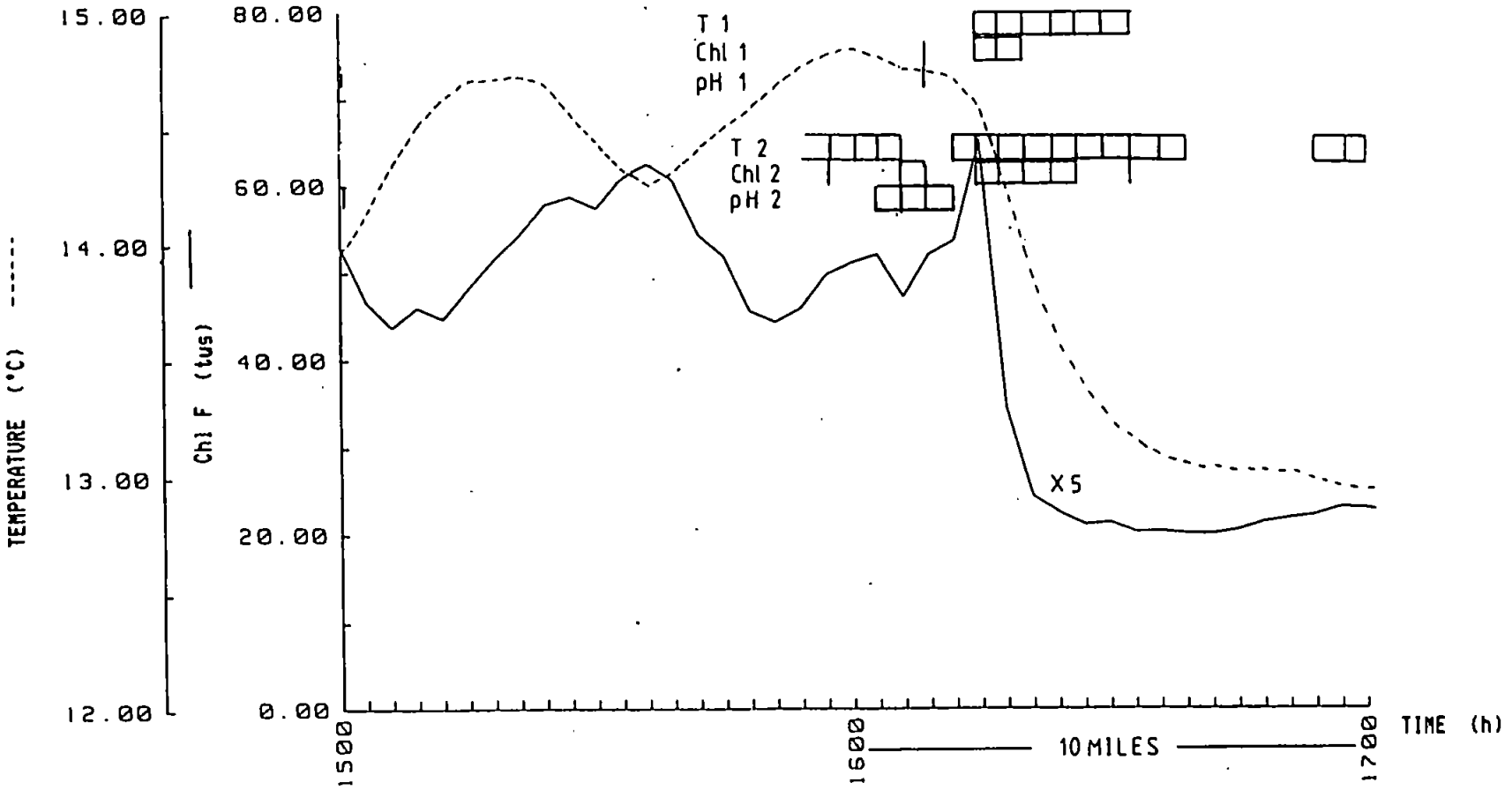


Figure 2.1.3. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) at crossing X5 of the Ushant front, 13 June 1984.

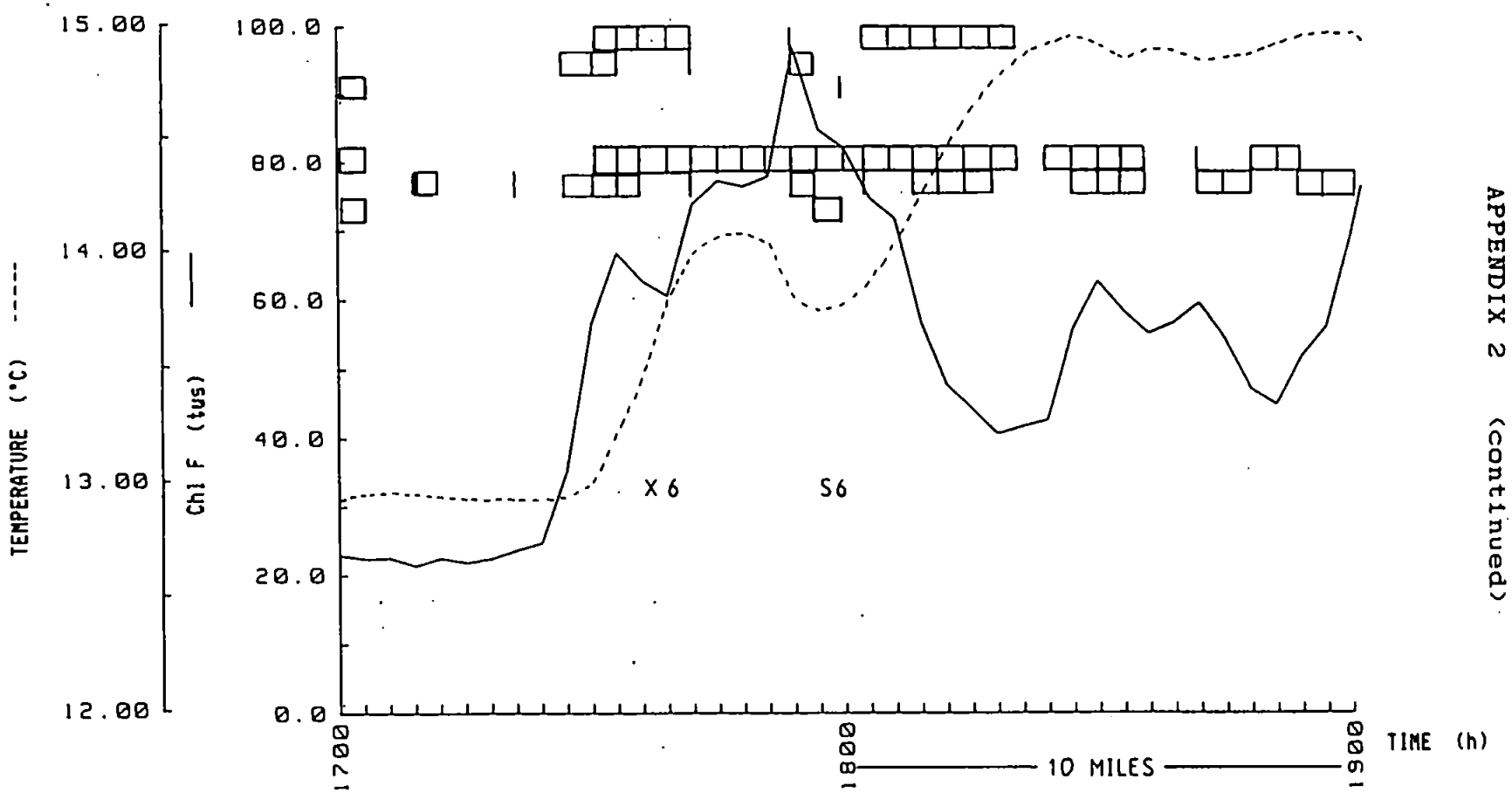
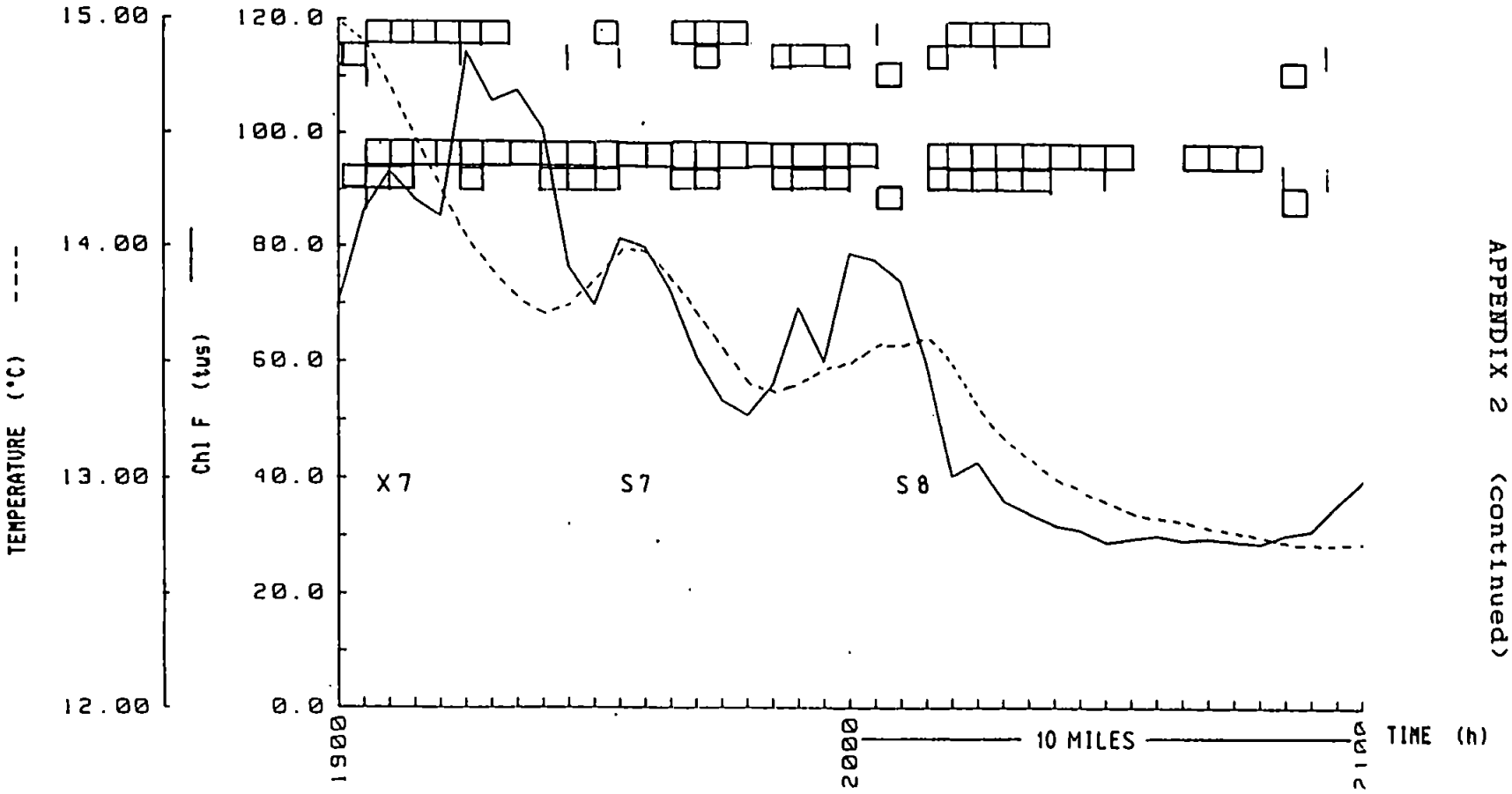


Figure 2.1.4. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) at skirting S6 and crossing X6 of the Ushant front, 13 June 1984.



APPENDIX 2 (continued)

Figure 2.1.5. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) at skirtings S7 & S8, and crossing X7 of the Ushant front, 13 June 1984.

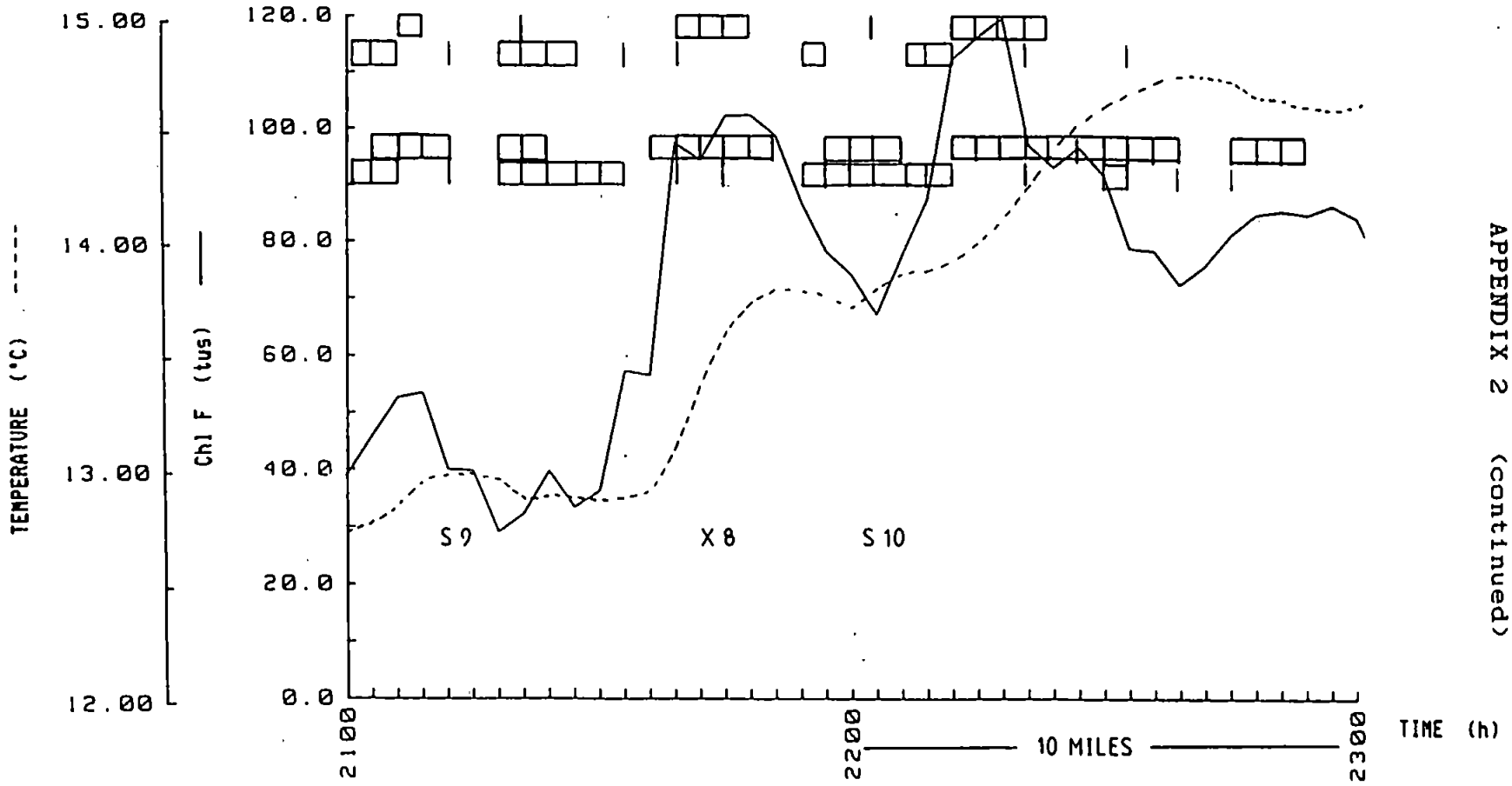


Figure 2.1.6. Alarm flags raised by T1 (0.5%), T2 (0.1%), C1 (10%), C2 (5%), pH1 (0.4%) and pH2 (0.3%) at skirting S9 & S10, and crossing X8 of the Ushant front, 13 June 1984.

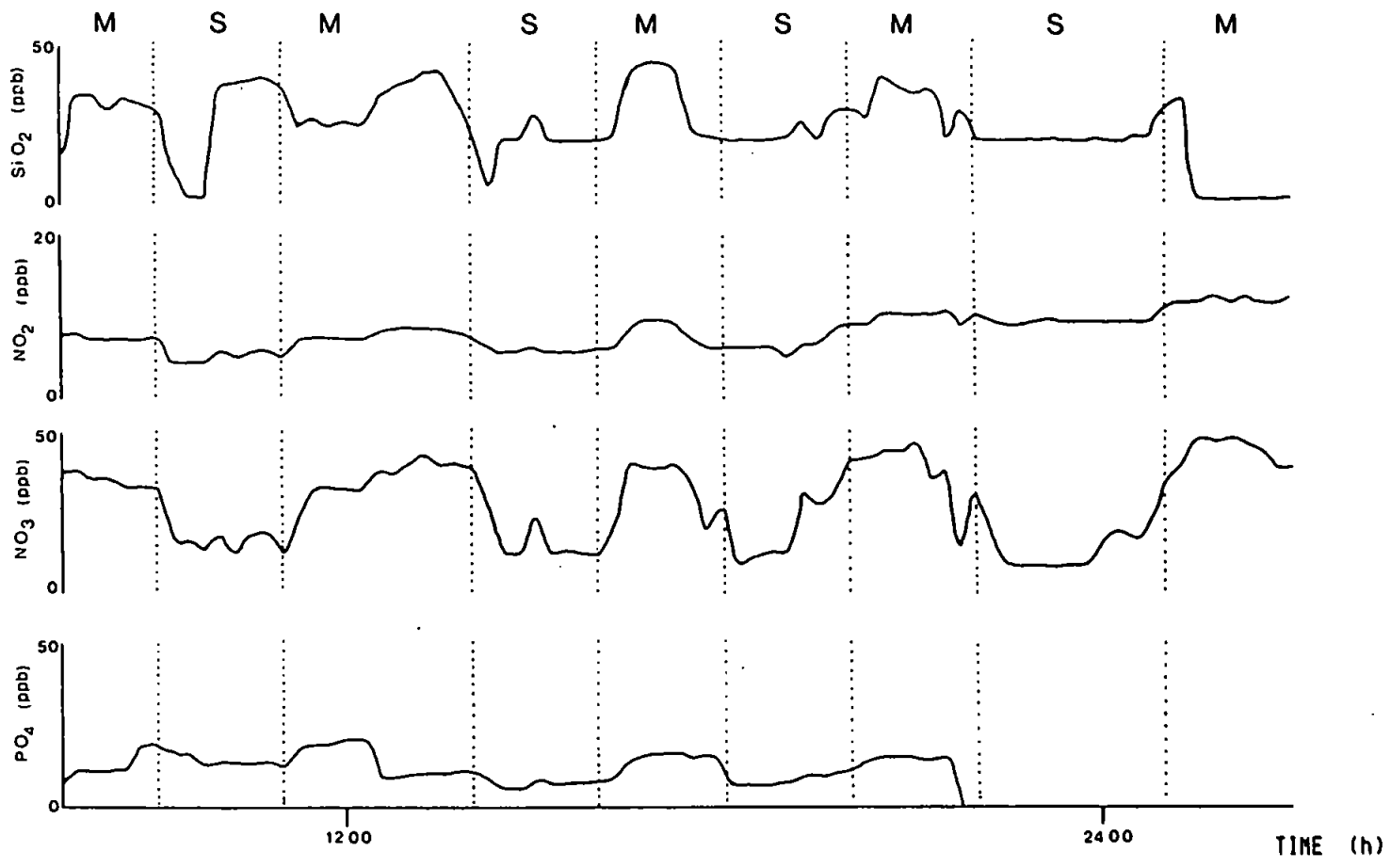


Figure 2.2.1. Distribution of phosphate, nitrate, nitrite and silicate at 3m across the Ushant front, 13 June 1984. M = mixed, S = stratified water.

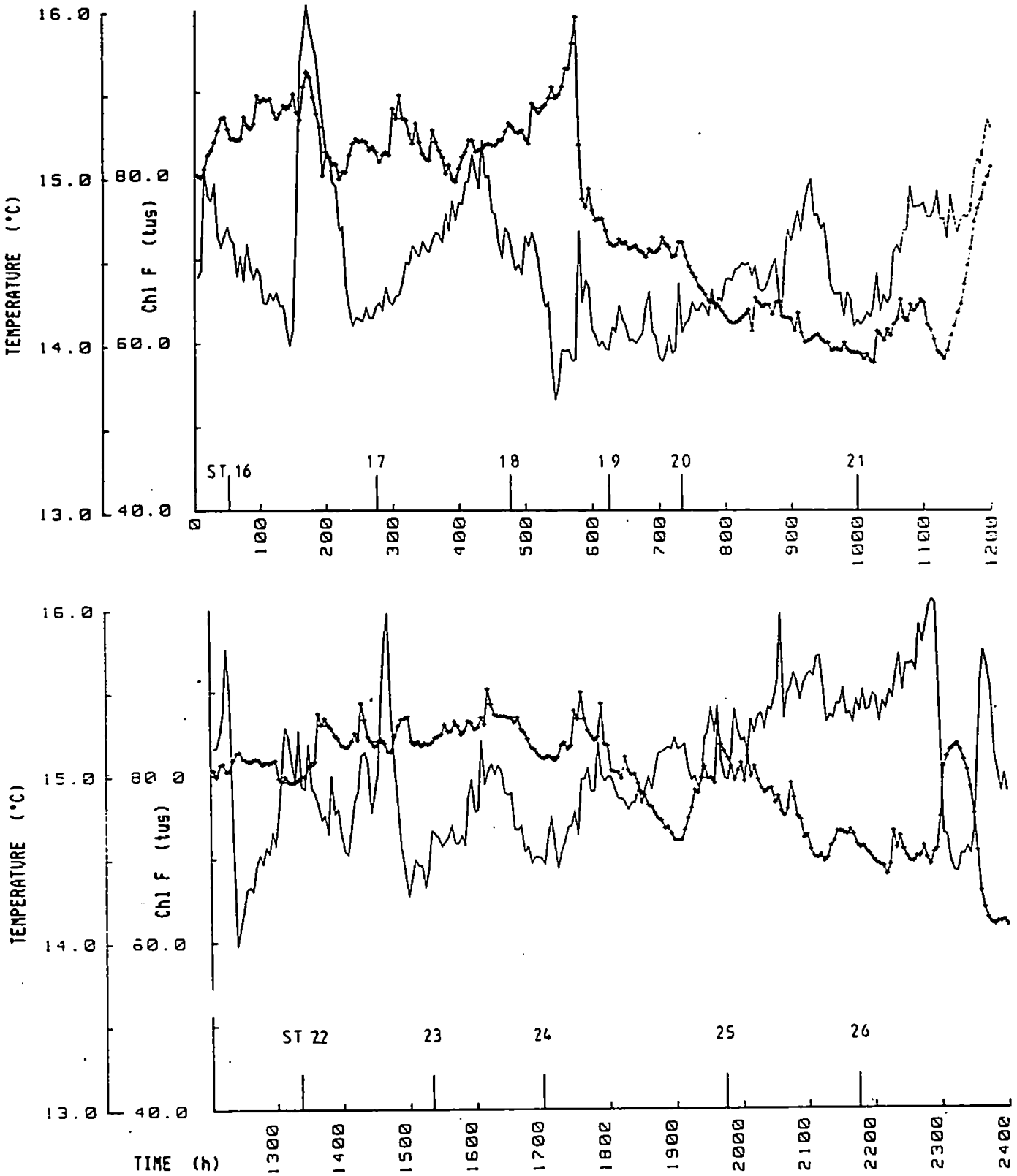


Figure 2.3.1. Distribution of temperature (°C) and Chl F (tus) at 3m across the Ushant front, 22 June 1984.

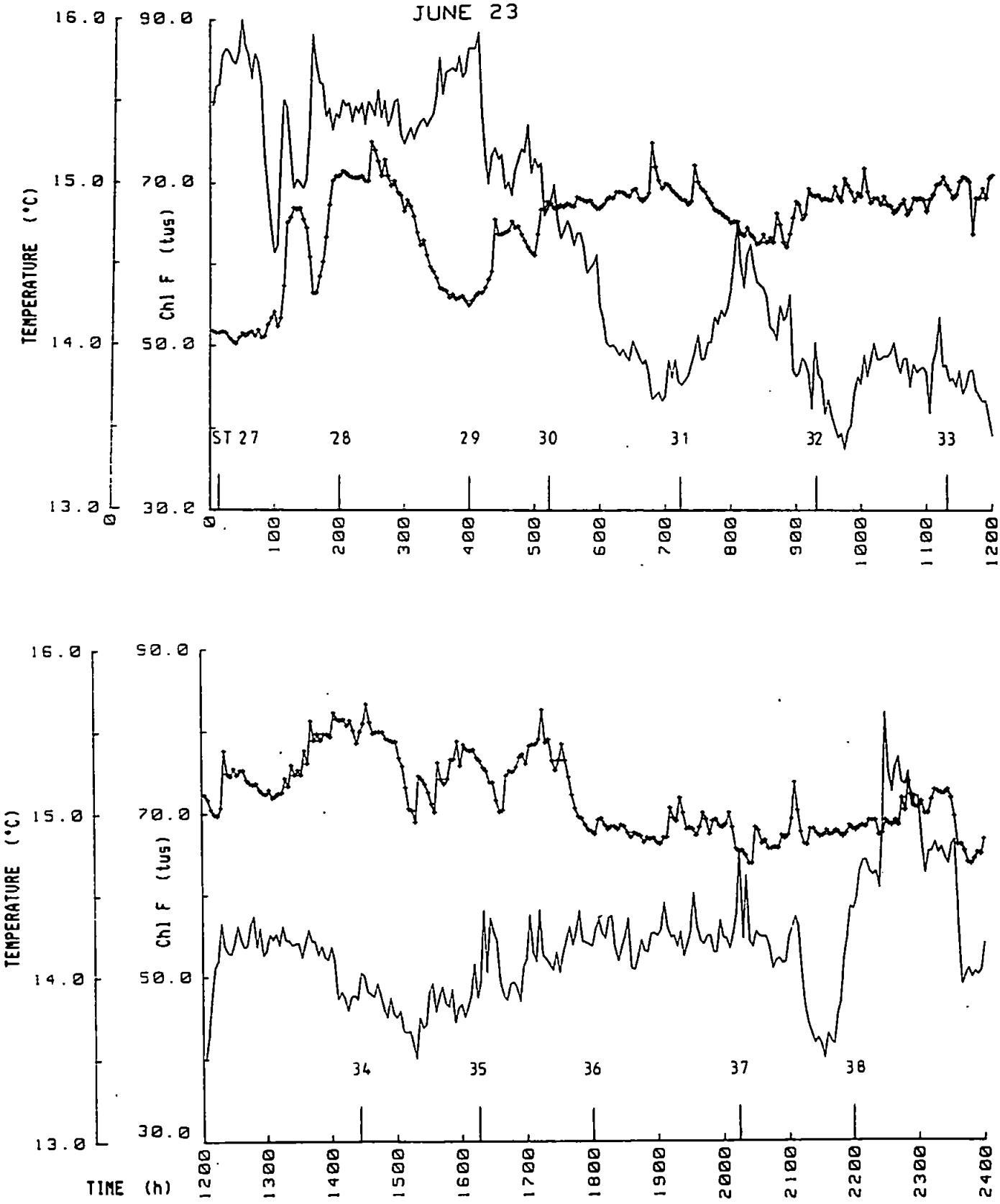


Figure 2.3.2. Distribution of temperature (°C) and Chl F (tus) at 3m across the Ushant front, 23 June 1984.

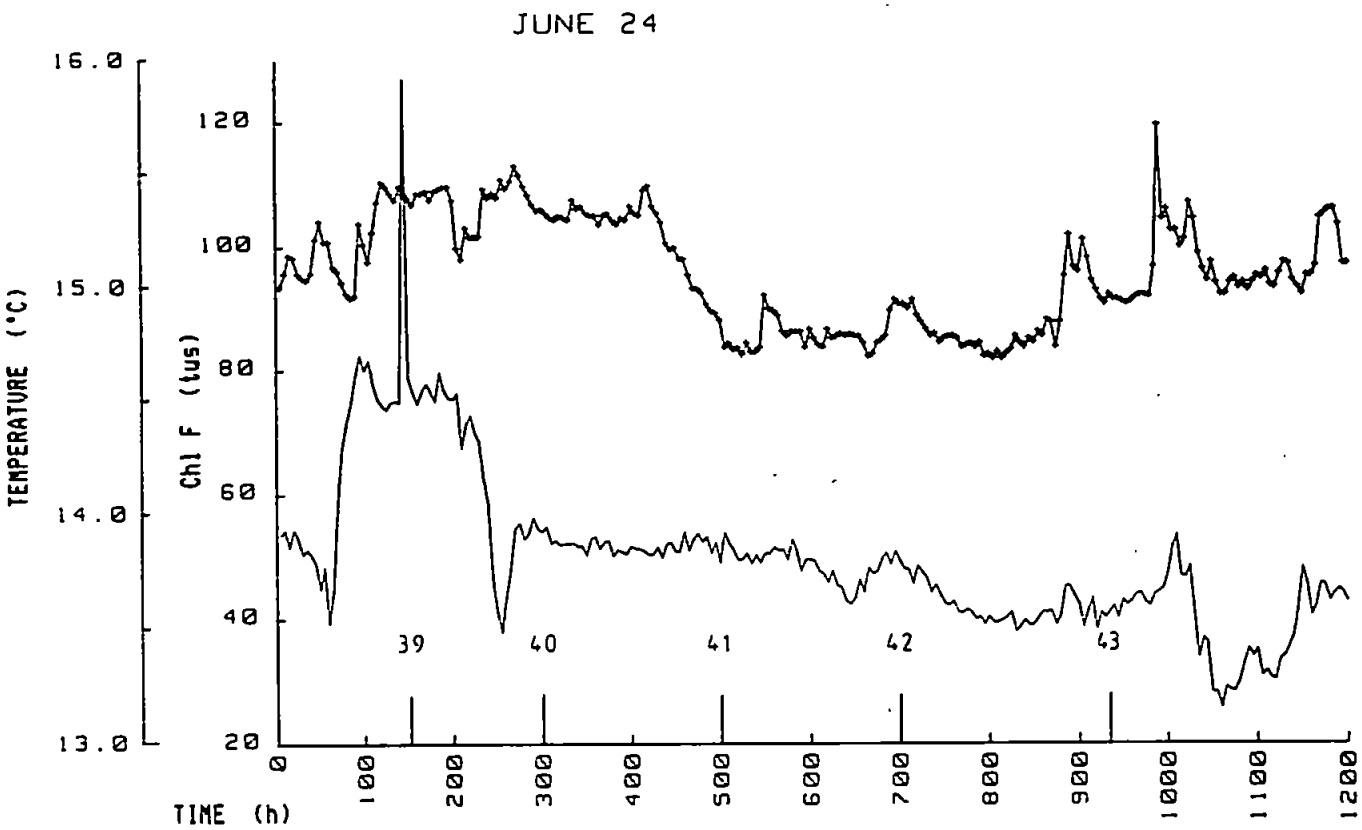


Figure 2.3.3. Distribution of temperature (°C) and Chl F (tus) at 3m across the Ushant front, 24 June 1984.

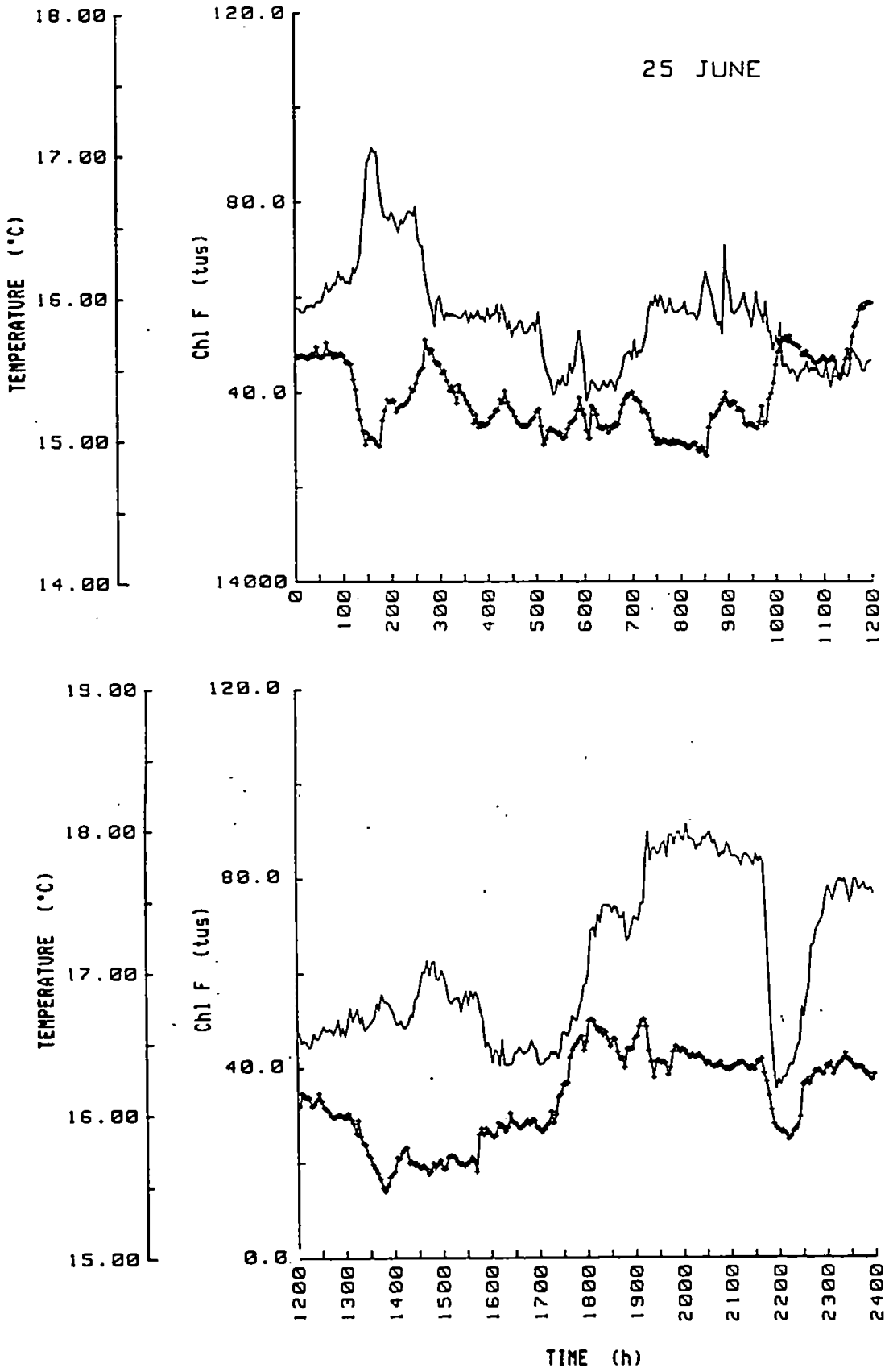


Figure 2.3.4. Distribution of temperature (°C) and Chl F (tus) at 3m across the Ushant front, 25 June 1984.

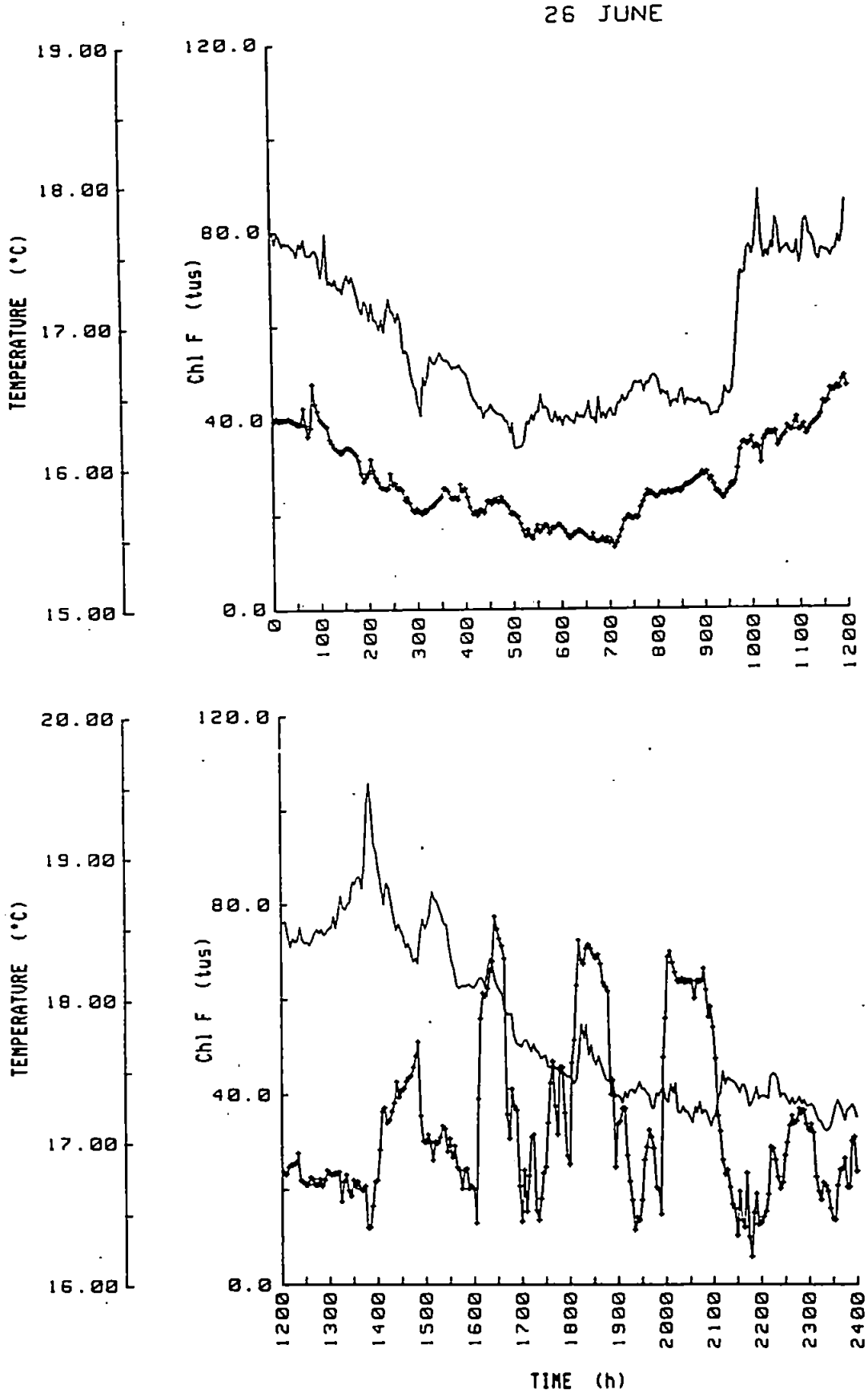


Figure 2.3.5. Distribution of temperature (°C) and Chl F (tus) at 3m across the Ushant front, 26 June 1984.

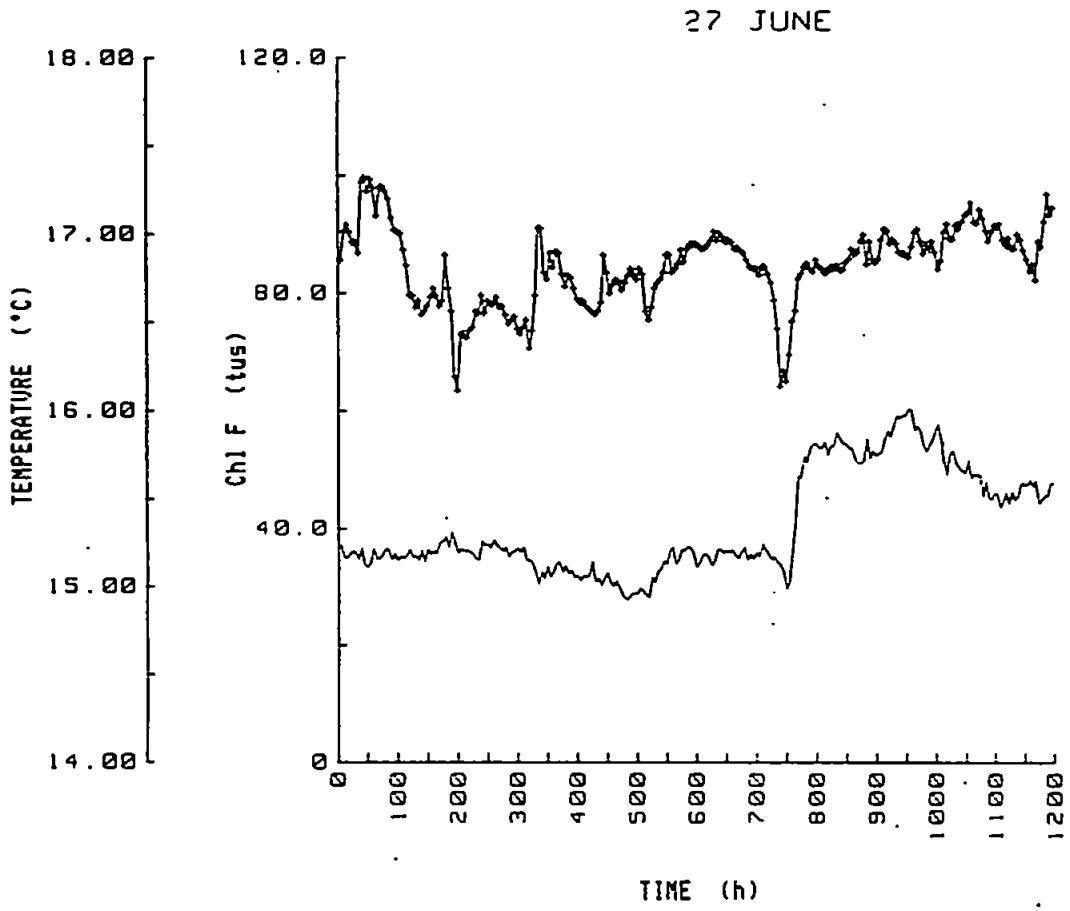


Figure 2.3.6. Distribution of temperature (°C) and Chl F (tus) at 3m across the Ushant front, 27 June 1984.

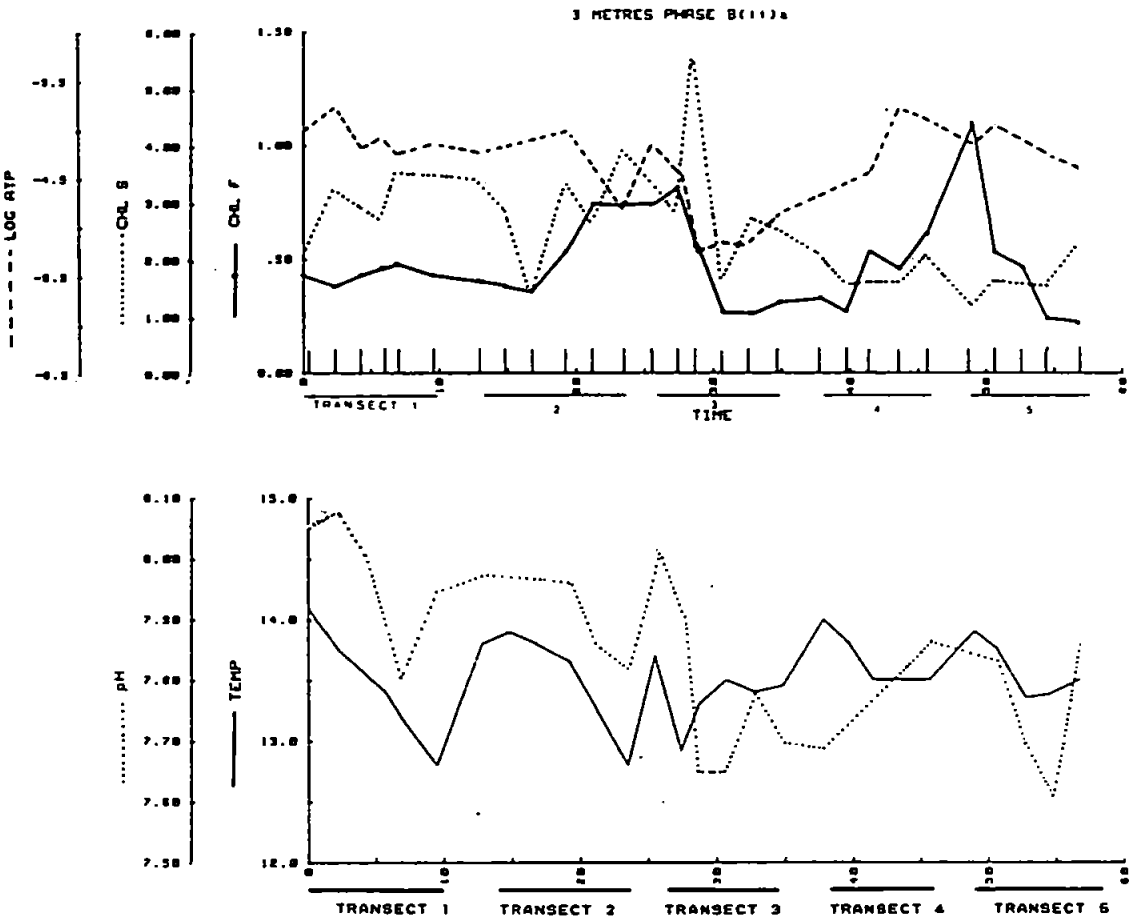


Figure 2.4.1. Distribution of (a) Log ATP, (b) Chl S (mg m^{-3}), (c) Chl F' (mg m^{-3}), (d) pH and (e) temperature (°C) at 3m for North/South Transects 1-5.

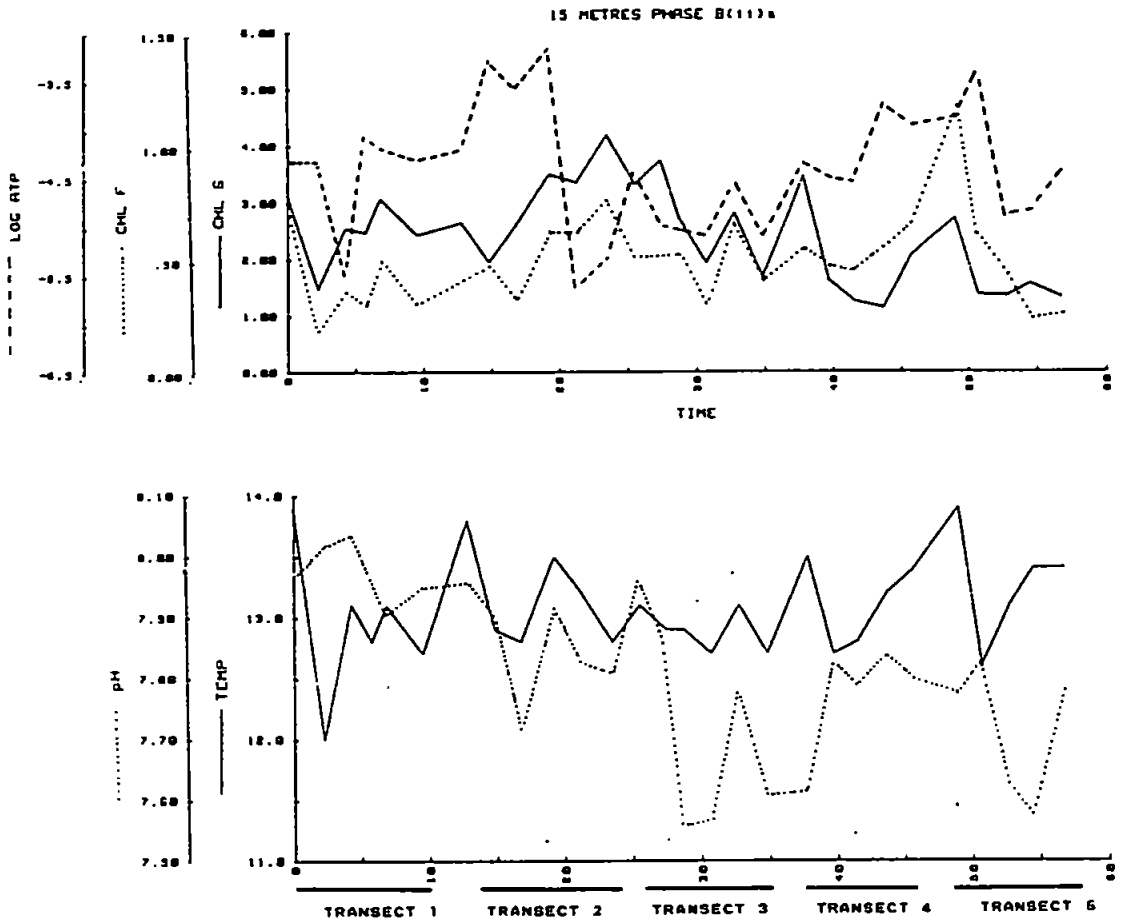


Figure 2.4.2. Distribution of (a) Log ATP, (b) Chl S (mg m^{-3}), (c) Chl F' (mg m^{-3}), (d) pH and (e) temperature (°C) at 15m for North/South Transects 1-5.

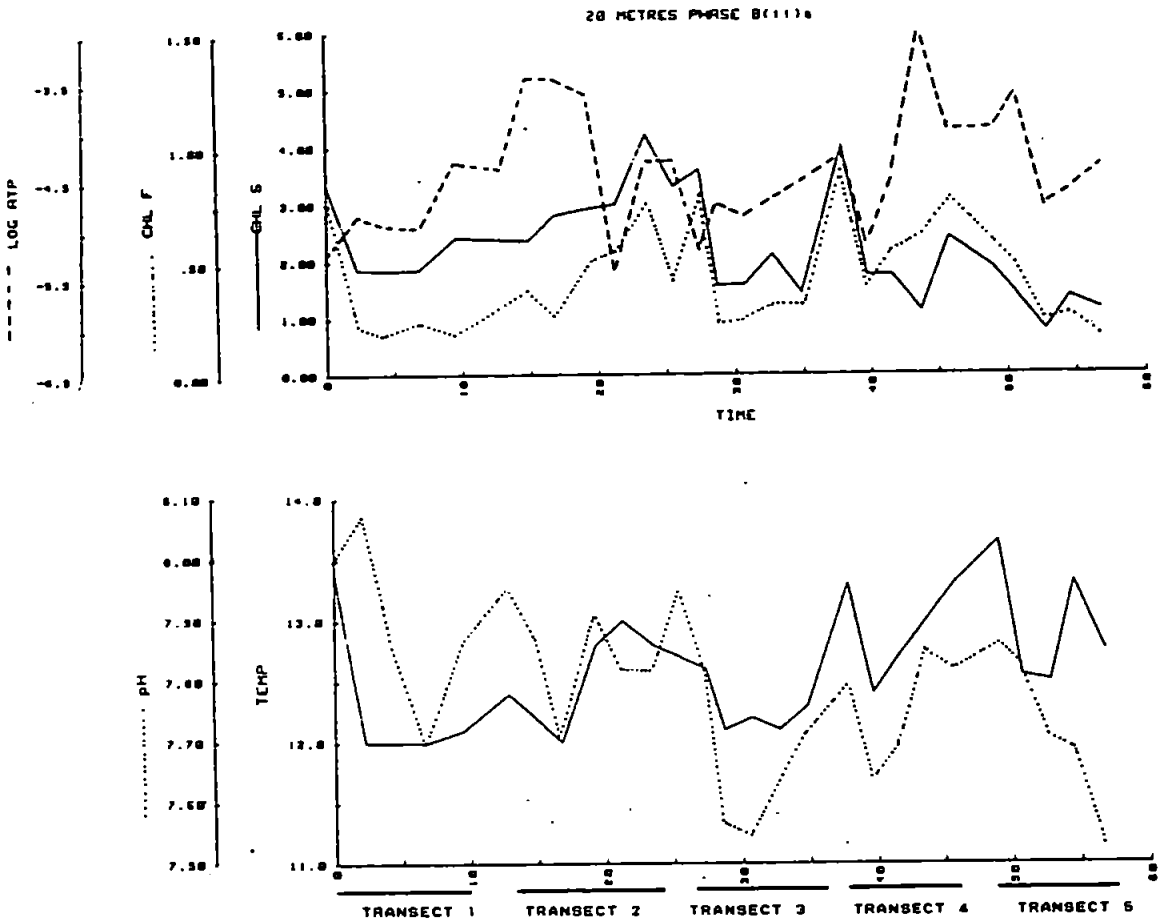


Figure 2.4.3. Distribution of (a) Log ATP, (b) Chl S (mg m^{-3}), (c) Chl F' (mg m^{-3}), (d) pH and (e) temperature (°C) at 20m for North/South Transects 1-5.

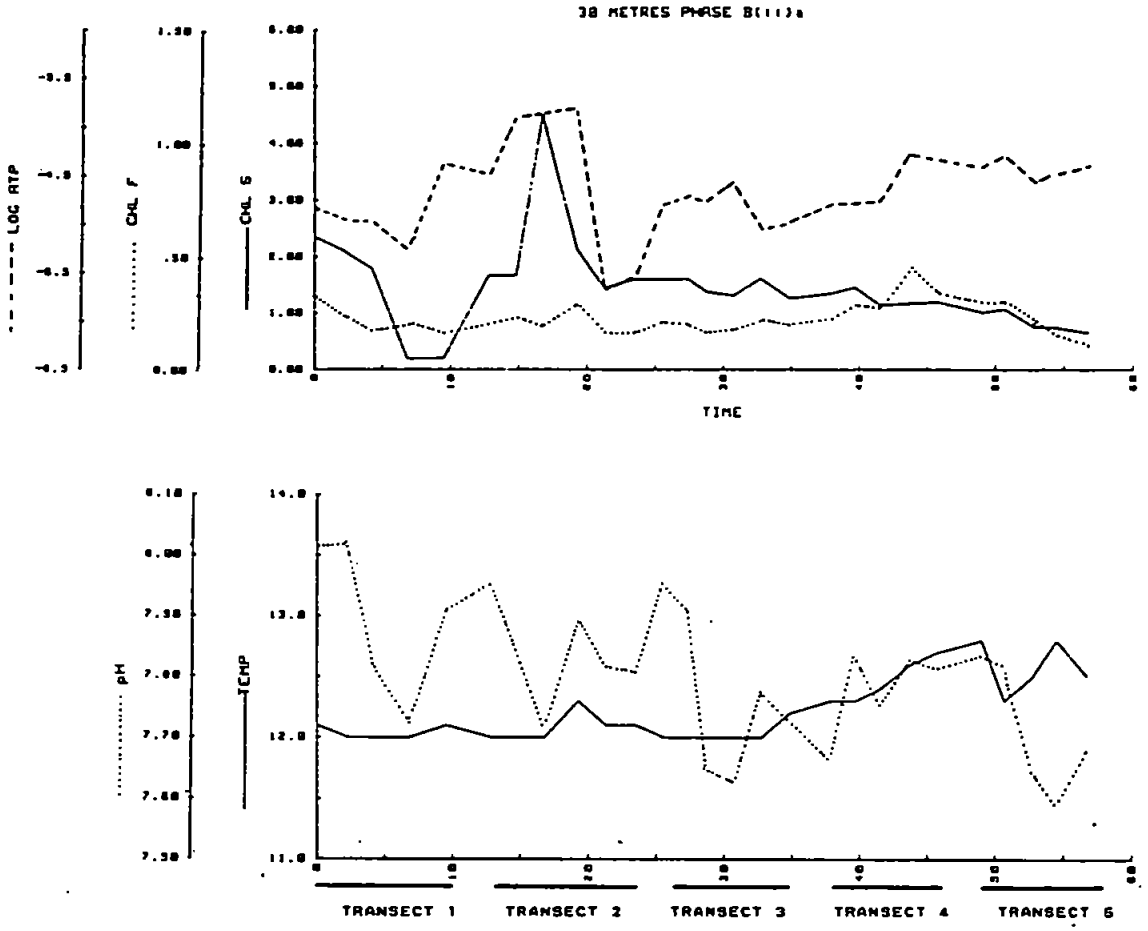


Figure 2.4.4. Distribution of (a) Log ATP, (b) Chl S (mg m^{-3}), (c) Chl F' (mg m^{-3}), (d) pH and (e) temperature (°C) at 30m for North/South Transects 1-5.

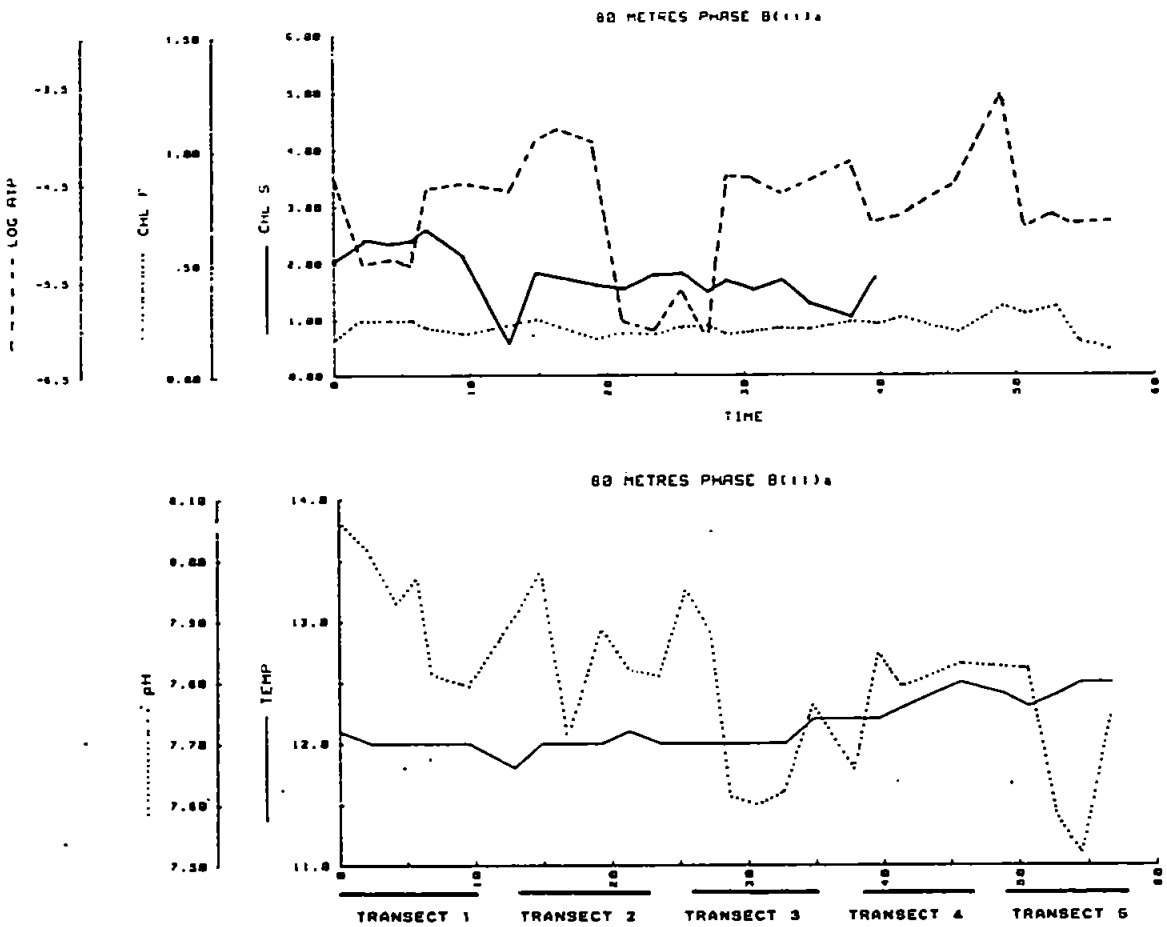


Figure 2.4.5. Distribution of (a) Log ATP, (b) Chl S (mg m^{-3}), (c) Chl F' (mg m^{-3}), (d) pH and (e) temperature (°C) at 80m for North/South Transects 1-5.

APPENDIX 3

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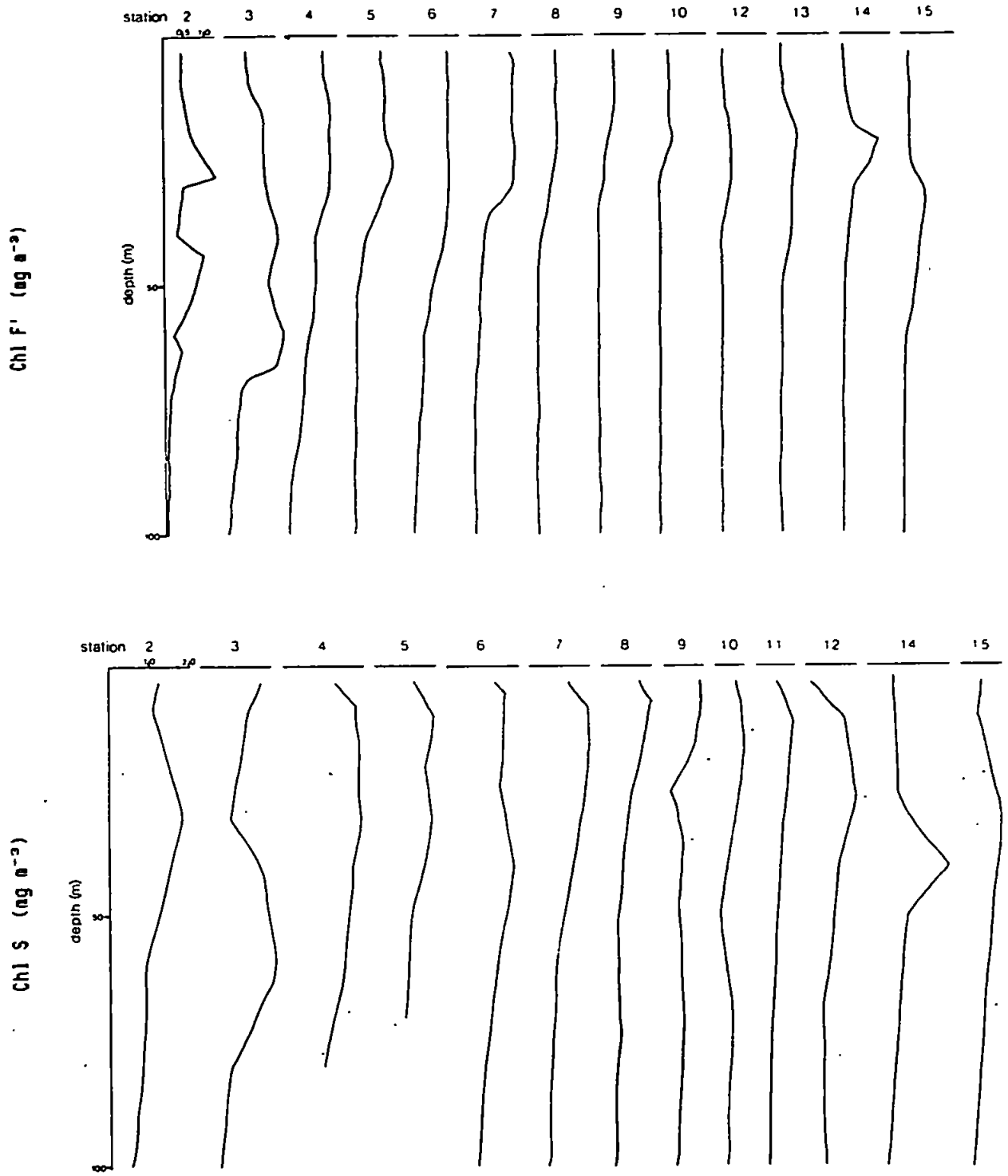

Figure 3.1.1. Little Sole Bank, 19-20 June 1984. Distribition of (a) Chl F' (mg m^{-3}) and (b) Chl S (mg m^{-3}) with depth (0-100m) at Profile Stations 2 to 15.

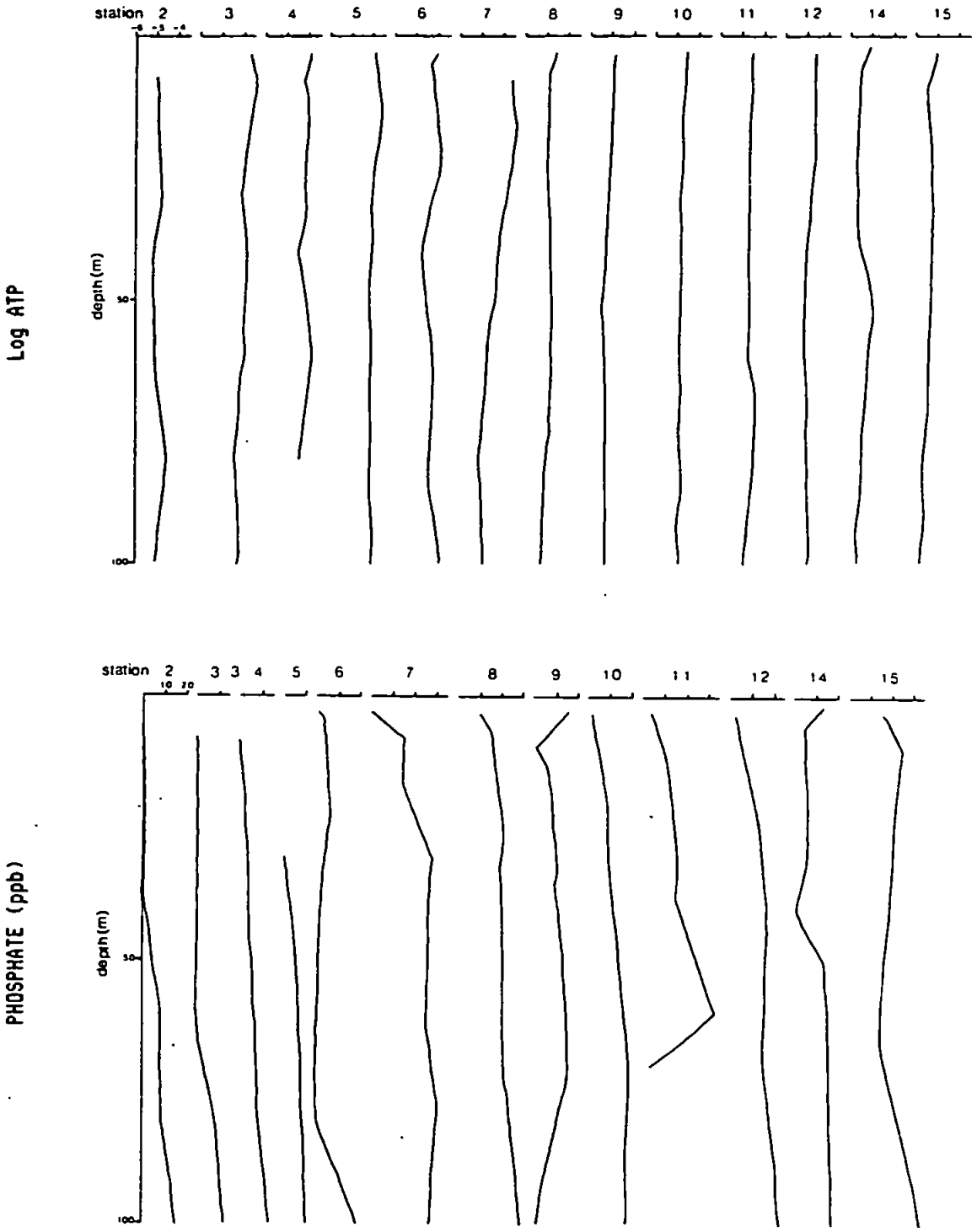

Figure 3.1.2. Little Sole Bank, 19-20 June 1984. Distribition of (a) Log ATP and (b) phosphate (ppb) with depth (0-100m) at Profile Stations 2 to 15.

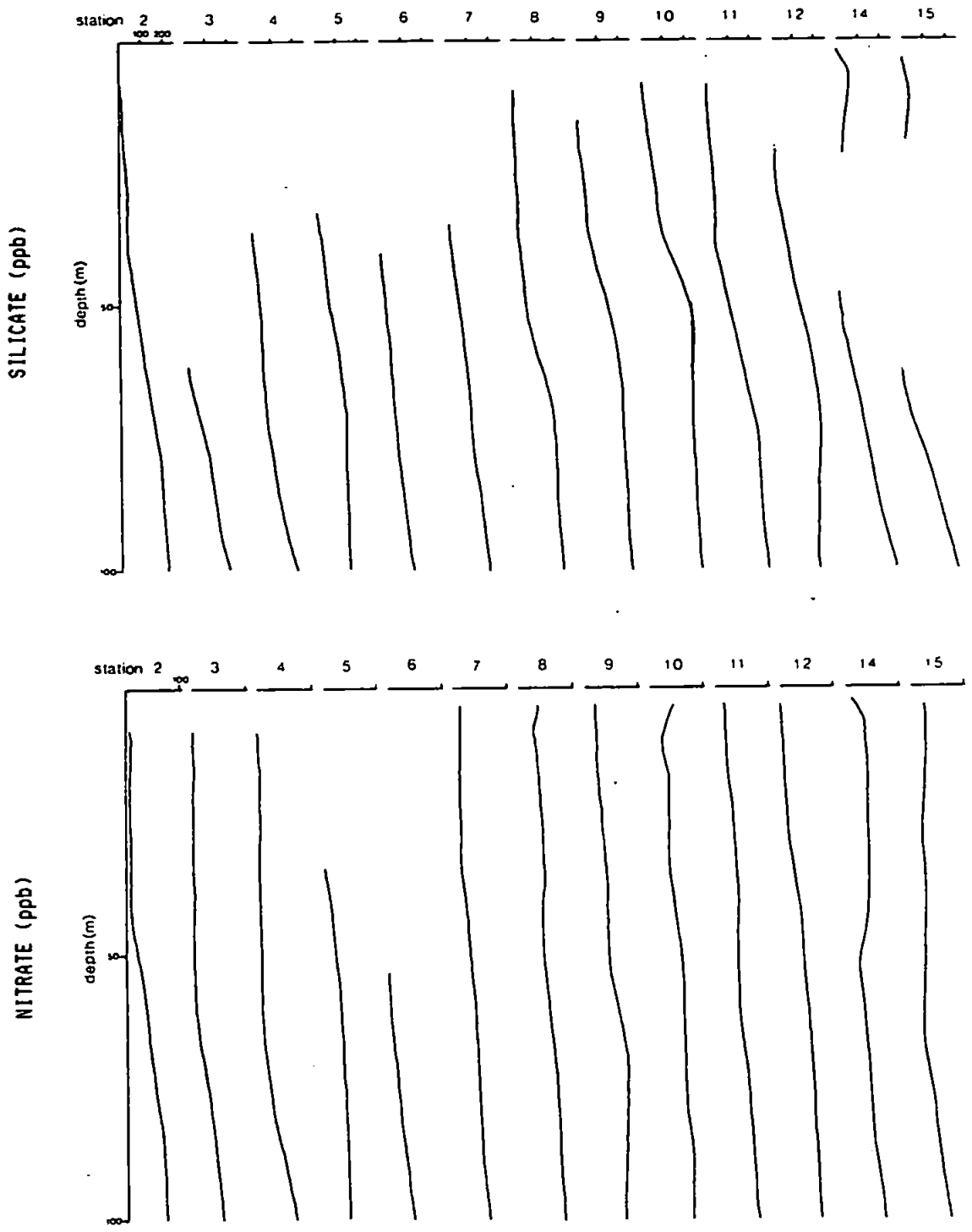

Figure 3.1.3. Little Sole Bank, 19-20 June 1984. Distribition of (a) nitrate (ppb) and (b) silicate (ppb) with depth (0-100m) at Profile Stations 2 to 15.

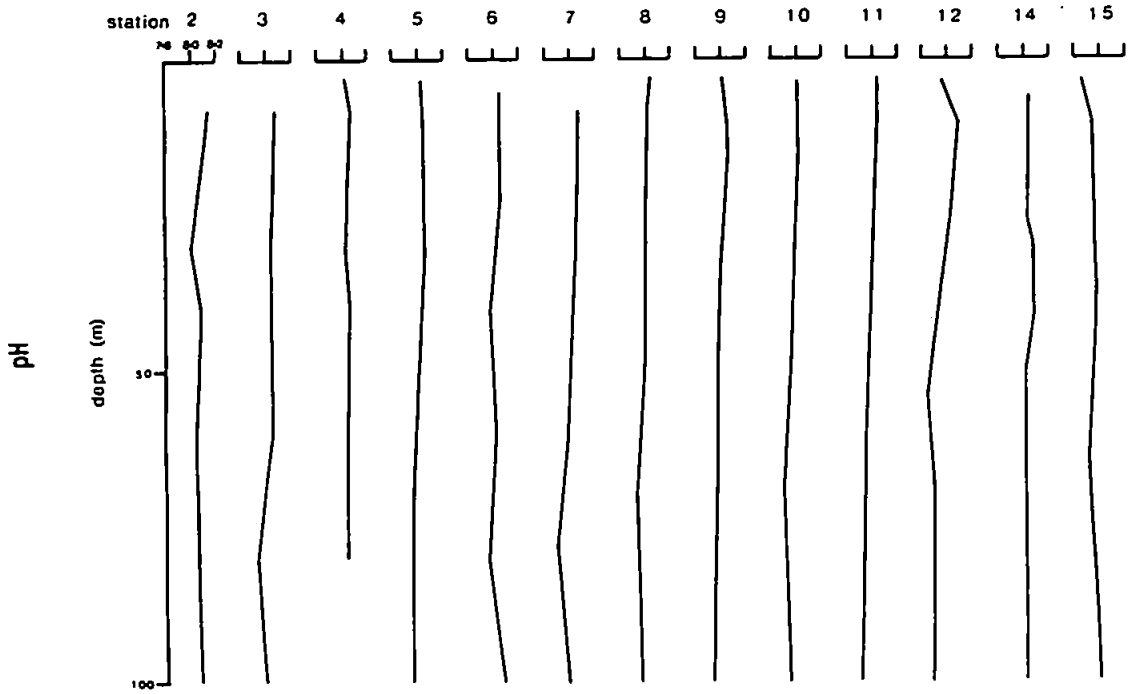

Figure 3.1.4. Little Sole Bank, 19-20 June 1984. Distribition of pH with depth (0-100m) at Profile Stations 2 to 15.