Ocean Time-Series Near Bermuda: Hydrostation S and the U.S. JGOFS Bermuda Atlantic Time-Series Study

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Abstract

Bermuda is the site of two ocean time-series programs. At Hydrostation S, the ongoing biweekly profiles of temperature, salinity and oxygen now span 37 years. This is one of the longest open-ocean time-series datasets and provides a view of decadal scale variability in ocean processes. In 1988, the U.S.JGOFS Bermuda Atlantic Time-series Study began a wide range of measurements at a frequency of 14-18 cruises each year to understand temporal variability in ocean biogeochemistry. On each cruise, the data range from chemical analyses of discrete water samples to data from electronic packages of hydrographic and optics sensors. In addition, a range of biological and geochemical rate measurements are conducted that integrate over time-periods of minutes to days. This sampling strategy yields a reasonable resolution of the major seasonal patterns and of decadal scale variability. The Sargasso Sea also has a variety of episodic production events on scales of days to weeks and these are only poorly resolved. In addition, there is a substantial amount of mesoscale variability in this region and some of the perceived temporal patterns are caused by the intersection of the biweekly sampling with the natural spatial variability. In the Bermuda time-series programs, we have added a series of additional cruises to begin to assess these other sources of variation and their impacts on the interpretation of the main time-series record. However, the adequate resolution of higher frequency temporal patterns will probably require the introduction of new sampling strategies and some emerging technologies such as biogeochemical moorings and autonomous underwater vehicles.

Introduction

Oceanic ecosystems exhibit variability on a wide range of time and space scales (Dickey, 1991, this volume). This variability is caused by a combination of physical and biological processes and has important consequences for the measurement and interpretation of the upper ocean carbon cycle. The most obvious temporal pattern is the seasonal variation in ocean mixing and phytoplankton primary production. Interannual variations in these seasonal patterns provide natural experiments on the relationship between the physical forcings and the biological response. Thus, long-term time-series observations provide a powerful tool for investigating biogeochemical processes in the ocean.

In 1988, the Bermuda Atlantic Time-series Study (BATS) was initiated as part of the U.S. Joint Global Ocean Flux Study (U.S.JGOFS) program. This station is one of two NSF funded time-series efforts in JGOFS, the second is the Hawaii Ocean Time-series Station (HOTS). The purpose of BATS and HOTS is coincident with the larger goals of JGOFS, namely "... to determine and understand ... the processes controlling the time-varying flux of carbon and associated biogenic elements in the ocean ..." (SCOR 1987). The focus of the BATS and HOTS efforts is on understanding the "time-varying" components of the ocean carbon cycle. The overall program is a mixture of traditional time-series monitoring of ocean processes and the application of specific process-oriented studies of ocean biogeochemistry within the time-series framework.

Bermuda is the site of numerous time-series investigations. One of the most prominent is the biweekly hydrographic sampling at Hydrostation S started by Henry Stommel and coworkers in 1954 (Schroeder and Stommel, 1969). This is one of the longest running ocean time-series operations in the world. From 1957-1963, this hydrographic study was supplemented by a program of biological and chemical measurements to determine the seasonal cycle of ocean production (Menzel and Ryther, 1960, 1961). This 5 year program provided the first detailed study of oceanic biogeochemistry in the Sargasso Sea. The data are still widely cited and reused to address hypotheses on the magnitude and controls of oceanic production (e.g., Platt and Harrison , 1985, Fasham et al., 1990). In addition to Hydrostation S, there is a 13 year time-series of deep-ocean sediment trap collections (Deuser, 1986) and a 12 year time-series of atmospheric measurements through the WATOX and AEROCE programs. This rich time-series history and these diverse existing measurement programs provide a valuable framework for the near-surface biogeochemistry investigations in the BATS program.

In this paper, we report on some of hydrography, oxygen, nutrients, pigments and particulate organic carbon and nitrogen and production rate data for the first three years of the BATS program. The data for the first two years are published elsewhere and discussed in greater detail (Michaels, submitted). These data illuminate some of the mechanisms that lead to the annual spring bloom in the Northern Sargasso Sea (Menzel and Ryther, 1960, 1961). In addition, the oxygen and nutrient data were used to provide independent estimates of the rates of new production associated with the 1989 spring bloom. We present new data on high-frequency variability in the time-series records that are likely due to mesoscale eddies. We also present some direct observations of these mesoscale features that indicate that both horizontal and vertical processes as involved in the delivery of nutrients to the surface. These unresolved features will require new and expanded sampling strategies and technologies to be resolved adequately. The BATS data provide important guidelines for the development of future time-series programs, particularly in the context of an extensive program like the proposed Global Ocean Observing System (GOOS)

Methods and Materials

Hydrographic sampling at Station S (Figure 1) began in 1954 with the routine measurement of temperature, salinity and oxygen at 24 depths (0-2600 m). Traditionally, temperature was measured using reversing thermometers, salinity by conductivity (recently with a Guildline, AutoSal) and oxygen by Winkler titration. Since 1988, these measurements have been made using the same methods as for the BATS station.

The Bermuda Atlantic Time-series Study (BATS) commenced monthly sampling in October, 1988 near the site of the Ocean Flux Program (OFP) station located 70 km southeast of Bermuda (Figure 1). This station is the present site of Dr. Werner Deuser's (WHOI) long-term deep-sea sediment trap mooring (Deuser, 1986). Cruises were conducted aboard the R.V. Weatherbird, R.V. Cape Henlopen and the R.V. Weatherbird II. On each BATS cruise, a free-drifting sediment trap array is deployed approximately 7 km southeast of OFP and all of the hydrocasts are started near this array. The 400 m array typically drifts between 10 and 50 km (occasionally 150 km) during the three-day deployment. The configuration of this array is described in Lohrenz, et al. (1992). On each cruise, hydrocasts and water bottle collections are made at 36-48 depths during a series of 4-7 casts from the surface to 4200 m. Details of the sampling scheme, analytical methods and quality control procedures are available in the BATS Methods Manual and data reports (Knap, 1991, 1992) and summarized below.

A Sea-Bird CTD with additional sensors was used to measure continuous profiles of temperature, salinity, dissolved oxygen, downwelling irradiance, beam attenuation and in situ fluorescence. This instrument package was mounted on a 12 position General Oceanics Model 1015 rosette that was typically equipped with twelve, 12 l Niskin bottles. The salinity and dissolved oxygen concentrations as calculated from the CTD sensors were calibrated with the discrete salinity and oxygen measurements collected from the Niskin bottles on the rosette (Michaels et al., submitted).

Water samples for oxygen, salinity and nutrient analyses usually were collected in teflon-coated Niskin bottles on the General Oceanics rosette. The oxygen samples were collected first. They were drawn into individually numbered, 115 ml BOD bottles and analyzed using the Winkler titration chemistry. Whenever possible, the samples were titrated with an automated titrator and endpoint detection system (MetrOhm 655 Dosimat, Oxygen Auto-Titrator). The duplication of oxygen samples at every depth allows a routine check on the precision of the oxygen measurement. Oxygen saturation was calculated from the Weiss algorithms (Weiss, 1970). Salinity samples were drawn after the gas samples and analyzed within 1 week of collection on a Guildline AutoSal 8400A salinometer. The samples were standardized to IAPSO Standard Seawater regularly during each sample run. Samples for nitrate+nitrite and phosphate were filtered with Whatman GF/F filters and frozen. Samples for silicate were filtered through 0.4 μm Nucleopore

filters and refrigerated at 4°C. The samples were analyzed within two weeks using traditional colorometric techniques (Strickland and Parsons, 1972).

Chlorophyll samples were filtered onto 25 mm GF/F filters, frozen in liquid nitrogen and analyzed by both fluorometric and HPLC techniques. Particulate organic carbon and nitrogen samples were filtered onto precombusted GF/F filters, dried and acidified under vacuum then analyzed on a Control Equipment Corp. 240-XA Elemental Analyzer and standardized using acetanilide as a reference standard.

Primary production is measured by the uptake of 14C in dawn to dusk in situ incubations. All the sampling employs trace-metal clean procedures. Incubations usually are conducted at 8 standard depths (20 m vertical spacing) in the upper 140 m. Details of the primary production methods are found in the BATS methods manual and in Lohrenz, et al., 1992)

Results

The time-series data at BATS are presented as time vs depth contour plots for some of the measured parameters (Figures 2-7). Surface seawater values were variable and showed an obvious seasonal pattern of winter mixing and a resultant spring bloom. The depth of the mixed layer showed a spring maximum in all three years and was followed by a rapid stabilization to a shallow summer mixed layer. Despite this similarity, there were significant differences between years in the intensity of winter mixing with 1989 and 1991 significantly stronger than 1990. These interannual differences are reflected in the biological parameters.

During the February 1989 spring bloom, oxygen concentrations were supersaturated from the surface to 250 m depth, whereas, in December 1988, the water was under saturated with oxygen at all depths. Following the 1989 bloom, oxygen anomalies continued to increase in the stratified surface waters and decreased below saturation in the lower euphotic and upper mesopelagic zones. Nutrient concentrations in the upper euphotic zone were uniformly low during most of the year. During the 1989 bloom sampling, the concentration of nitrate+nitrite in the mixed layer reached values of 0.5 to 1.0 μmoles/kg. Phosphate and silicate concentrations did not show a seasonal increase during this period. During the winter and spring of 1990, the oxygen concentration in the mixed layer was always above saturation. Despite the 170 m mixed layer, which should have entrained water with measurable nutrients, nitrate+nitrite was near the detection limit of 0.05 μmoles/kg during the spring 1990 cruises. There was some depletion of nitrate between 100 and 150 m during the February 1990 cruise in the period of deepest mixing. The bloom in 1991 was of similar intensity to that in 1989, but lasted for a much longer period of time. Oxygen concentrations were slightly above saturation early in the bloom and increased as it progressed. As with 1989, the supersaturation extended to the base of the 200 m mixed layer. There was measurable nitrate in the euphotic zone for over three months.

In addition to the spring mixing events, there were small surface maxima in nitrate+nitrite concentrations in September, October and November 1989. These elevated surface nutrients may be due to rainfall inputs from summer storms and hurricanes, although they occurred after the summer minimum in salinity. Coincident with these surface nutrients, there were anomalously high nutrients near 60 m in both October and November, 1989.

Each spring bloom was characterized by the presence of elevated stocks of chlorophyll a, particulate organic carbon (POC) and particulate organic nitrogen (PON, Figures 5-7). Despite the relatively recent mixing, the concentration of chlorophyll a in February 1989 was a factor of 10 higher than the upper euphotic zone chlorophyll concentration the rest of the year. By the next sampling period (March 26, 1989), the subsurface chlorophyll maximum had descended to 100 m. This maximum became less pronounced through the summer. Particulate organic carbon and nitrogen were also elevated by a factor of 10 at the surface during the 1989 bloom. As with chlorophyll, the surface POC and PON returned to typical values by March. However, unlike the chlorophyll, POC and PON did not show a marked subsurface maximum.

The spring bloom in 1990 also was characterized by elevated concentrations of chlorophyll a and particulate organic matter between February and April, 1990. The peak 1990 chlorophyll concentration was 40% of the peak 1989 value of 0.5 µg/kg. Peak POC and PON concentrations were 20-35% lower than the peak values in 1989.

The bloom in 1991 was very different in the pattern of particulate materials. Although the chlorophyll concentration does increase to values of greater than 0.5 ug/kg, this increase happens in the June-September period, well after the depletion of nutrients. Particulate organic carbon and nitrogen peak values are more synchronous with the nutrient depletion and again, are concentrated near the surface.

The rate of phytoplankton primary production as measured by the uptake of 14C also shows a seasonal pattern synchronous with the winter mixing (Figure 8). However, the seasonal variations in the production rates are at odds with the relative strength of each bloom as interpreted from the intensity of the mixing. The period of high production is short in 1989 (a single cruise) while it is more prolonged during 1990, the winter with the shallowest mixed layer. Production in spring 1991 is the highest of the three spring periods, but again, elevated production lasts past the period of nutrient inputs. In addition, there are periods of high production during the late summer, traditionally thought to be a time of low production. The June-July production peaks in 1989 are before the anomalous surface nutrients observed that fall. The high production in 1990 lasts much of the fall period and is not accompanied by observable nutrient inputs.

Short-term Variability in Phytoplankton Community Composition

The HPLC pigment data indicated major differences in phytoplankton community structure between biweekly cruises in 1990 (Figure 9a-l, also see Michaels et al., submitted). The interpretation of these pigment profiles is presented in detail elsewhere (Michaels et al., submitted). The important feature for the purposes of this paper are the large variations in the vertical structure of different pigments between the cruises. Each of these pigments is characteristic of one or more groups of phytoplankton. For example, in early May, the chlorophyll b peak at 100 m was associated with elevated zeaxanthin concentrations at the same depth, suggesting the presence of prochlorophyte-like phytoplankton. In early April, there is no corresponding zeaxanthin peak at 100 m, indicating the chlorophyll b was associated with eukaryotic chlorophytes and/or prasinophytes, and not prokaryotic prochlorophyte-like phytoplankton. Some pigments, (fucoxanthin, chlorophyll c1+2, chlorophyll c3, diadinoxanthin and diatoxanthin) were present throughout the bloom period. Sometimes they co-occurred with 19'-hexanoyloxyfucoxanthin and 19'-butanoyloxyfucoxanthin, suggesting that prymnesiophytes and chrysophytes (respectively) were present. At other times, elevated levels of fucoxanthin, diadinoxanthin and diatoxanthin concentrations were observed without high levels of 19'-hexanoyloxyfucoxanthin and 19'-butanoyloxyfucoxanthin, a possible indication of diatom-dominated blooms.

Horizontal Heterogeneities in Nitrate

In November, 1991, we occupied a grid of 20 stations (4 by 5 grid) 20 minutes apart in both longitude and latitude (Figure 10) and made profiles of hydrography and nutrients. There was considerable spatial heterogeneity in these profiles, even on the same density surface. Figure 10a shows the nitrate concentration on the 26.16 sigma-theta density surface and figure 10b shows the depth of that density surface. There are changes of more than 1 mmol/kg over horizontal distances of 15-30 km. At some of these locations, this density surface changes depth by as much as 40 m in the vertical over the same horizontal scale. There will be eddy diffusion of nutrients along these gradients on the isopycnal surface and in some cases, the depth changes of the surface will cause a vertical nutrient flux by isopycnal mixing.

Discussion

The data collected through the U.S JGOFS, Bermuda Atlantic Time-series Study (BATS) can be used to provide guidance on the development of future ocean time-series programs and the Global Ocean Observing System. These data illustrate some of processes that control the upper ocean carbon cycle and the temporal and spatial complexities of even an oligotrophic ocean environment. When coupled with the 37 year Hydrostation S record, they also indicate the substantial problems of determining long-term secular trends in a complex and

variable ocean. More detailed interpretations of these data will be presented elsewhere (Michaels, et al., submitted). Here, we examine the importance of these sampling issues for the creation and interpretation of a time-series program.

The first 36 months of data collected in the Bermuda Atlantic Time-series Study show the marked seasonality that was initially described by Menzel and Ryther (Menzel and Ryther, 1960, 1961) and is evident in the analyses of the 37 year Hydrostation S record (e.g.Jenkins and Goldman, 1985). It seems likely that the seasonal aspects of the data do reflect the larger scale temporal patterns of ocean biogeochemical processes. The higher resolution pigment data indicate either that there is a great deal of high-frequency community evolution at this site, or, more likely, that there is a complex mesoscale eddy field that is being randomly sampled by the BATS program. This horizontal complexity is also evident from the 20 station grid of profiles that show variation in nutrient profiles on density surfaces.

Surface Ocean Seasonal Pattern

Menzel and Ryther (1960, 1961) first documented the seasonal pattern of mixing, biomass and production in the Sargasso Sea at Hydrostation S, 45 km northwest of the BATS site. Surface cooling and wind mixing in the winter and spring caused the formation of a mixed layer that eroded into the nutrient rich layers below the euphotic zone and introduced those nutrients into the euphotic zone. These nutrients then stimulated a bloom of phytoplankton and a period of increased primary production which lasted from 1 to 3 months. They noted substantial interannual variability in the timing and intensity of the bloom (Menzel and Ryther, 1961), which they related to variations in the intensity of deep mixing in the winter. The marked seasonality of the ocean near Bermuda is now firmly established from the 37 year Hydrostation S record. Jenkins and Goldman (1985) analyzed an 18 year portion of this record. There is a significant decadal scale variability in the record with a period of lower ventilation in the mid 1970's bracketed by periods of strong ventilation in the early 1960's and the late 1970's (Jenkins and Goldman, 1985). A more recent analysis shows that the early 1980s were a period of very low ventilation with winter mixed layers of less than 80 m (Figure 11). In the late 1980s (1983-1989), leading up to the BATS sampling, the mixed layers of approximately 150 m were shallow compared to the historical values.

New production is defined as the phytoplankton primary production supported by the uptake of exogenous nutrients (Dugdale and Goering, 1967) primarily nitrate in ocean systems. Over time scales where steady state assumptions are appropriate, the amount of new production will be equal to the exports of organic nitrogen from the euphotic zone, either from sinking particles (Eppley and Peterson, 1979), downward mixing of DON (Jackson, 1988, Toggweiler, 1990) or the vertical migration of zooplankton (Longhurst and Harrison, 1988). At the BATS station, new production rates have been estimated by the changes in oxygen and nitrate

concentrations during the February 1989 bloom (Michaels, et al., submitted). These rates were 19-44 % of the annual average new production of 0.5 moles N/ m2/yr estimated by Jenkins and Goldman (1985). The estimates of new production in this single event also equal or exceed the annual particle export as estimated by short-term sediment trap deployments (Lohrenz, et al., 1992) at the same station. With both nitrate and oxygen, these are underestimates of the new production associated with this event. Similar short-term production events are also noticeable in the BIOWATT mooring data from a location west of Bermuda (Dickey, 1991). Clearly, if it is actually a product of temporal variation, spring bloom events like this one would account for a significant proportion of the annual new production.

These blooms occur nearly every year with substantial interannual variability in intensity of the deep mixing. The mixing in 1989 was less than the long-term average (Figure 11). The intensity of deep-winter mixing and the depth of the mixed layer should both be related to the amount of biological new production that occurs. As in 1989, this winter mixing probably accounts for the majority of the annual new production. The accurate characterization of these blooms in both time and space will be required to assess the annual rates of regional new production. A more highly resolved temporal sampling may be necessary to understand the biological and physical mechanisms that determine the timing and magnitude of the bloom. The complete characterization of the carbon and nitrogen systems will also be required, in particular, the currently unknown stocks of dissolved organic matter.

Spatial Variability

Both the high-frequency pigment profiles and the 20 station grid in November 1991 shed light on some of the difficulties of making and interpreting time-series measurements in a heterogeneous ocean. Every cruise in spring 1990 measured a different phytoplankton community. If the changes on phytoplankton community structure was truly a temporal pattern, it would indicate a very dynamic system. However, it is much more likely that these short-term changes are the intersection of our sampling program with the natural spatial variability in this region. We may be sampling a different eddy on each cruise. Thus these higher frequency data are difficult to interpret as a coherent time-series.

The 20 station grid shows much the same feature. There are significant changes in the nutrient fields over spatial scales of 10's of kilometers. These data also indicate that there are processes that are not resolved adequately with one-dimensional sampling programs. Calculations of the vertical supply of nutrients by diapynal mixing and isopycnal mixing along the tilted isopycnal surfaces suggest that at times, most of the nutrient supply to the base of the euphotic zone come from isopycnal mixing. The 4-5 order of magnitude differences in the vertical gradients is balanced by the 4-6 order of magnitude differences in eddy diffusivities. A full understanding of the time-varying nutrient fluxes that control the ocean

carbon cycle will require that all of the important processes be resolved. Creation of time-series sampling programs will require consideration of these issues and the application of appropriate sampling strategies to cover the appropriate scales for each region.

Suggestions for the Future

The BATS sampling program yields a consistent view of the large-scale seasonal patterns in the upper ocean carbon cycle. Between the BATS and Hydrostation S sampling programs, there are approximately hydrographic 40 cruises each year to the area southeast of Bermuda. Yet, despite this intense sampling effort, it is apparent that some important biogeochemical features are not resolved adequately. The spatial heterogeneity of the environment causes some aliasing of the temporal signal. In addition, there are some processes that are fundamentally horizontal, such as the isopycnal nutrient inputs to the euphotic zone that cannot be resolved with a one-dimensional time-series program.

There are new and emerging ocean sampling technologies that may significantly improve our resolution of ocean variability and resolve some of the time and space scales that alias a traditional time-series program. Moorings can provide very high resolution temporal signals to show the contribution of low frequency, short-duration events (see Dickey, this volume). Satellites provide extensive spatial and temporal coverage of near surface properties with some weather limitations. Autonomous Underwater Vehicles (AUV) allow for repeated, high-frequency three-dimensional surveys of a region (see Dickey, this volume). AUVs have the additional advantage that water samples can be routinely returned to the laboratory for analysis. This expands the range of measurements that can be made with an AUV compared to truly remote technologies (i.e. moorings). However, for many measurements, there are still no appropriate remote sensors and human beings and ships will be required.

Prior to the establishment of a time-series sampling program, estimates must be made of the temporal and spatial scales that are important for the scientific questions of the study and for the specific region of study. Logistical constraints must also be considered. From this information, a sampling strategy can be determined that both addresses the scientific questions and resolves the relevant temporal and spatial scales. For some environments and questions, a truly one-dimensional approach may be appropriate and some combination of moorings and traditional hydrographic sampling could be employed. In heterogeneous areas, satellites and three-dimensional mapping using AUVs or ships would be required. The required frequency of sampling as determined from the temporal scale of the processes might determine the choice of traditional ship-board sampling or autonomous vehicles. In all of these decisions, logistics (especially distance to the station and availability of a research vessel) and costs must be taken into account so that the sampling strategy yields the most relevant information for the cost.

The existing US.JGOFS Time-series stations in Bermuda and Hawaii are valuable examples of the power and potential of time-series observations for addressing globally important questions. Understanding the patterns and controlling processes of temporal changes in ocean biogeochemistry is a necessary component of any attempt to understand the role of the oceans in global processes. These stations are also natural test beds for the development of remote technologies for time-series research. Efforts to test and evaluate mooring and AUV technologies at the US.JGOFS Time-series stations are part of the future plans for these sites and some efforts have already begun. Theses simultaneous validations of remote and traditional technologies are an important first step in developing the sampling strategies that will be the heart of a Global Ocean Observing System.

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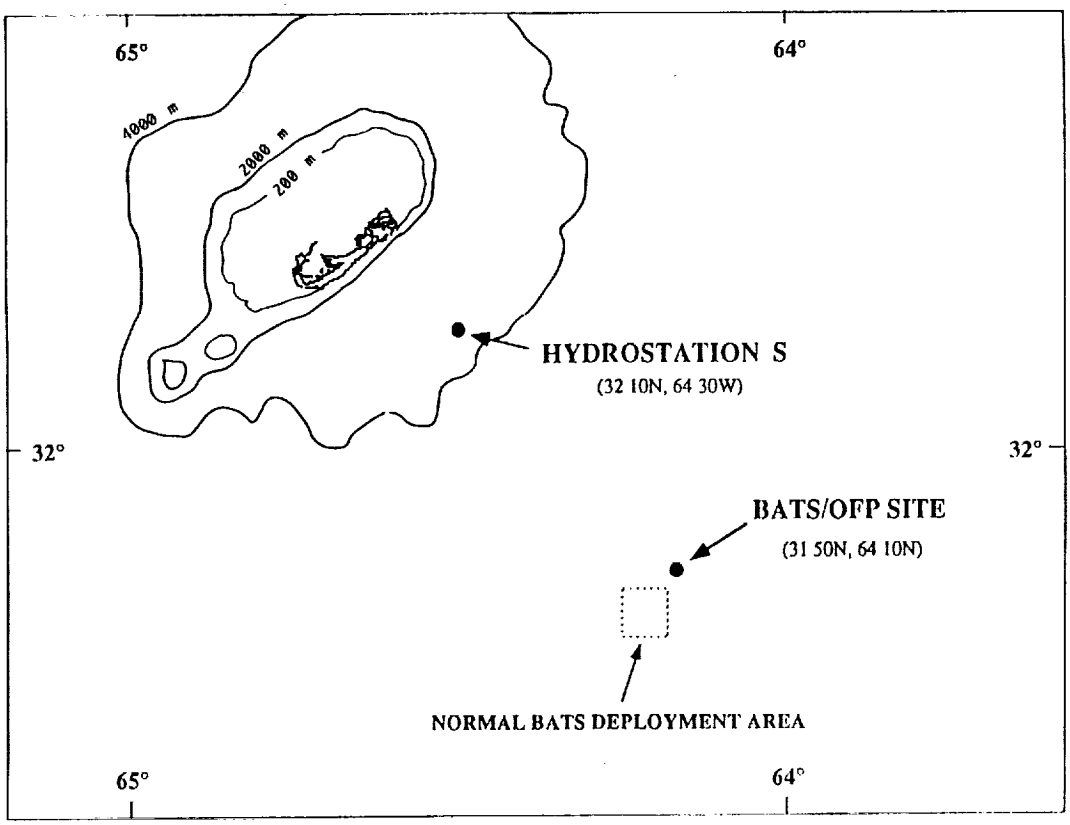


Figure 1. Map of Bermuda and the surrounding waters illustrating the location of the Bermuda Atlantic Time-series Study (BATS) site and the site of the Hydrostation S sampling (1954-present).

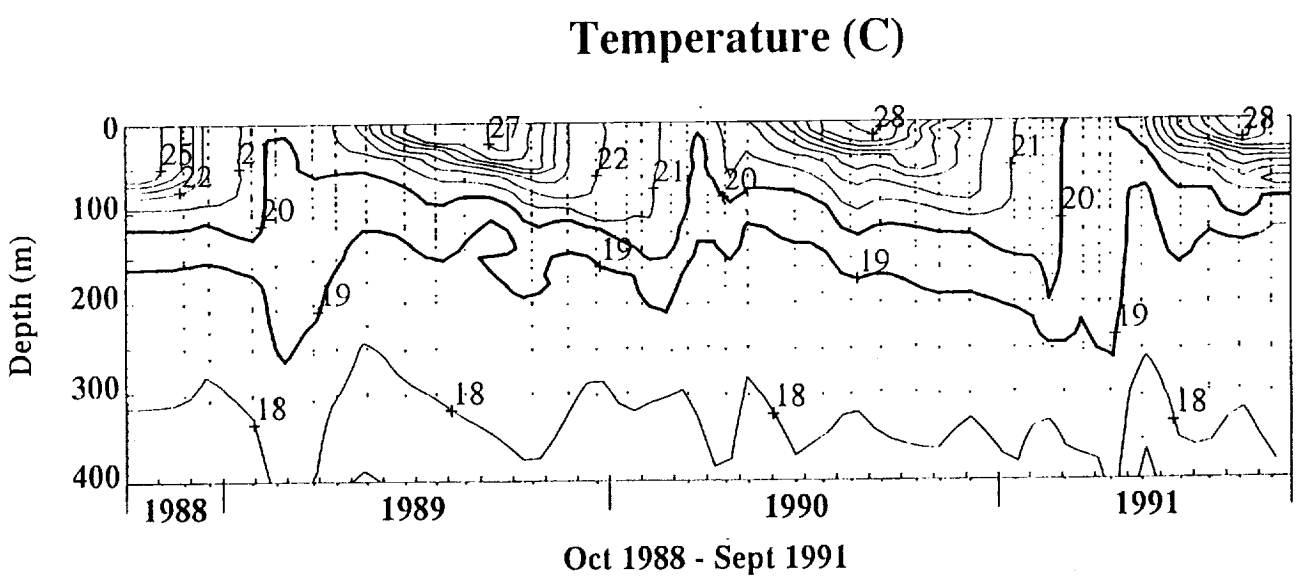


Figure 2. Contour plot of potential temperature (°C) at the BATS site during the first three years of sampling.

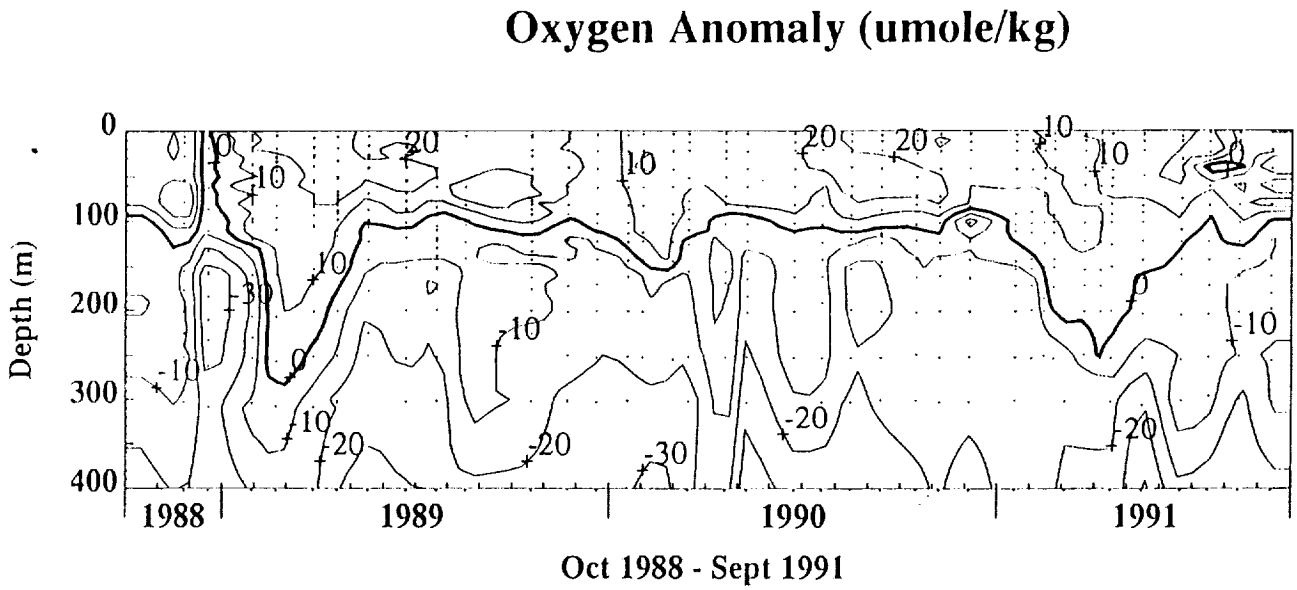


Figure 3. Contour plot of Oxygen Anomaly (μmoles/kg) at the BATS site. Oxygen anomaly is defined as the difference between the measured oxygen concentration and the calculated saturation concentration of oxygen at the in situ temperature and salinity.

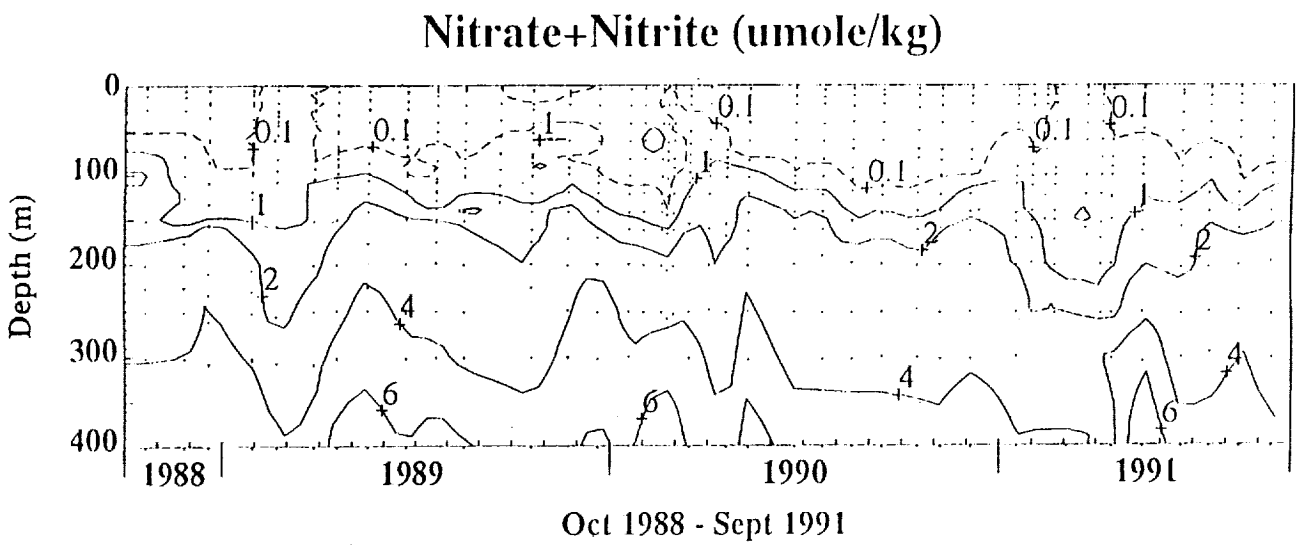


Figure 4. C ontour plot of Nitrate+Nitrite (µmols/kg) at the BATS site.

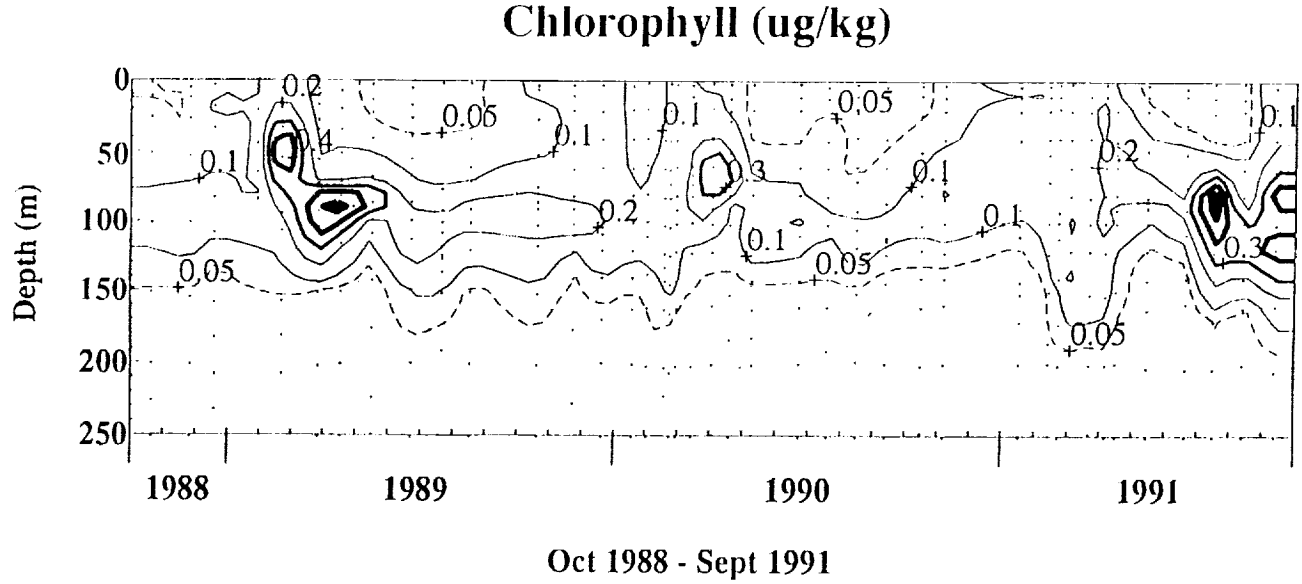


Figure 5. Contour plot of Chlorophyll a (µg/kg) measured using fluorometric techniques. In March, 1990 the fluorometric method was changed (see methods).

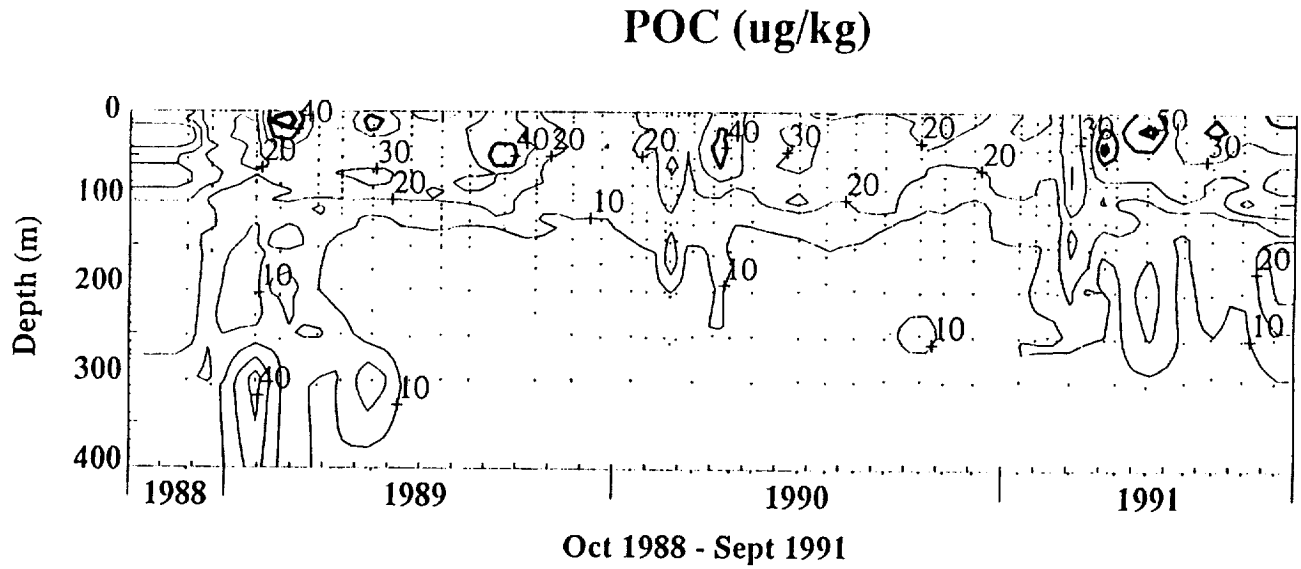


Figure 6. Contour plot of Particulate Organic Carbon (µg/kg) at the BATS site.

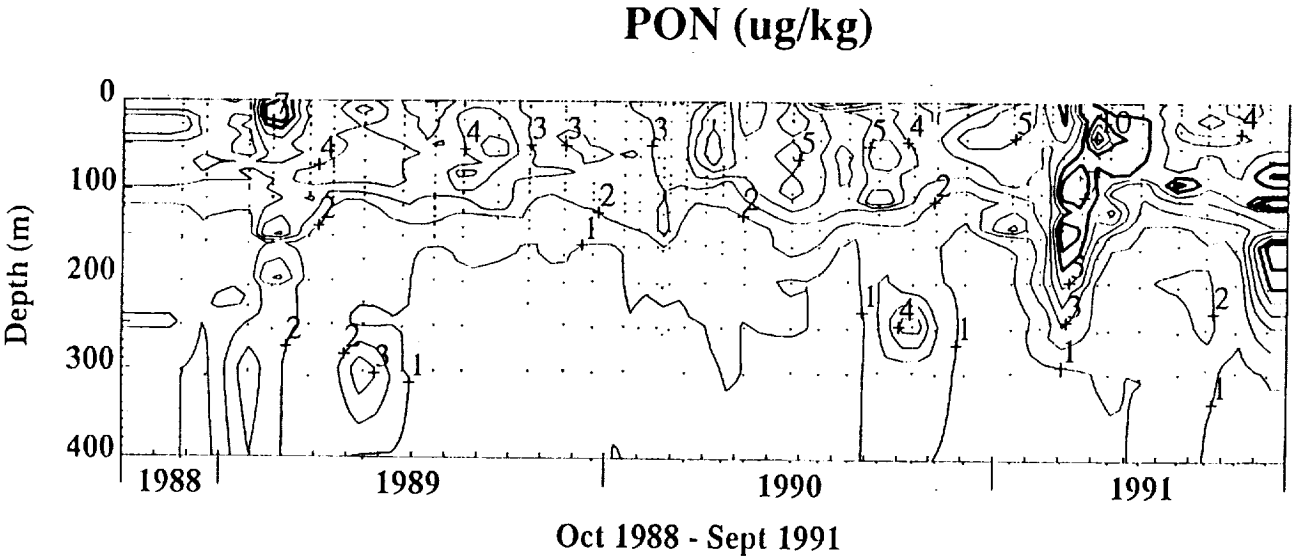


Figure 7. Contour plot of Particulate Organic Nitrogen (µg/kg) at the BATS site.

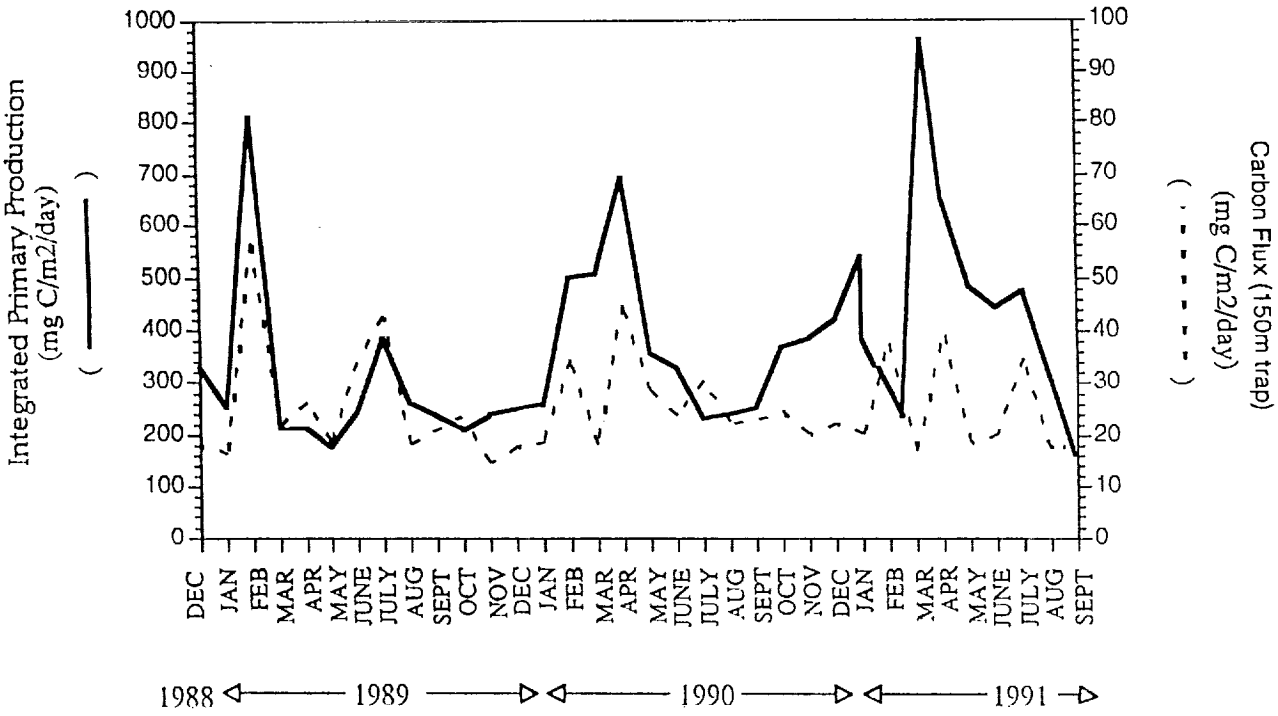


Figure 8. The integrated Primary Production (0-150 m) and sediment trap estimated carbon flux at 150 m at the BATS site. Data for the first two years are also found in Lohrenz et al., 1992.

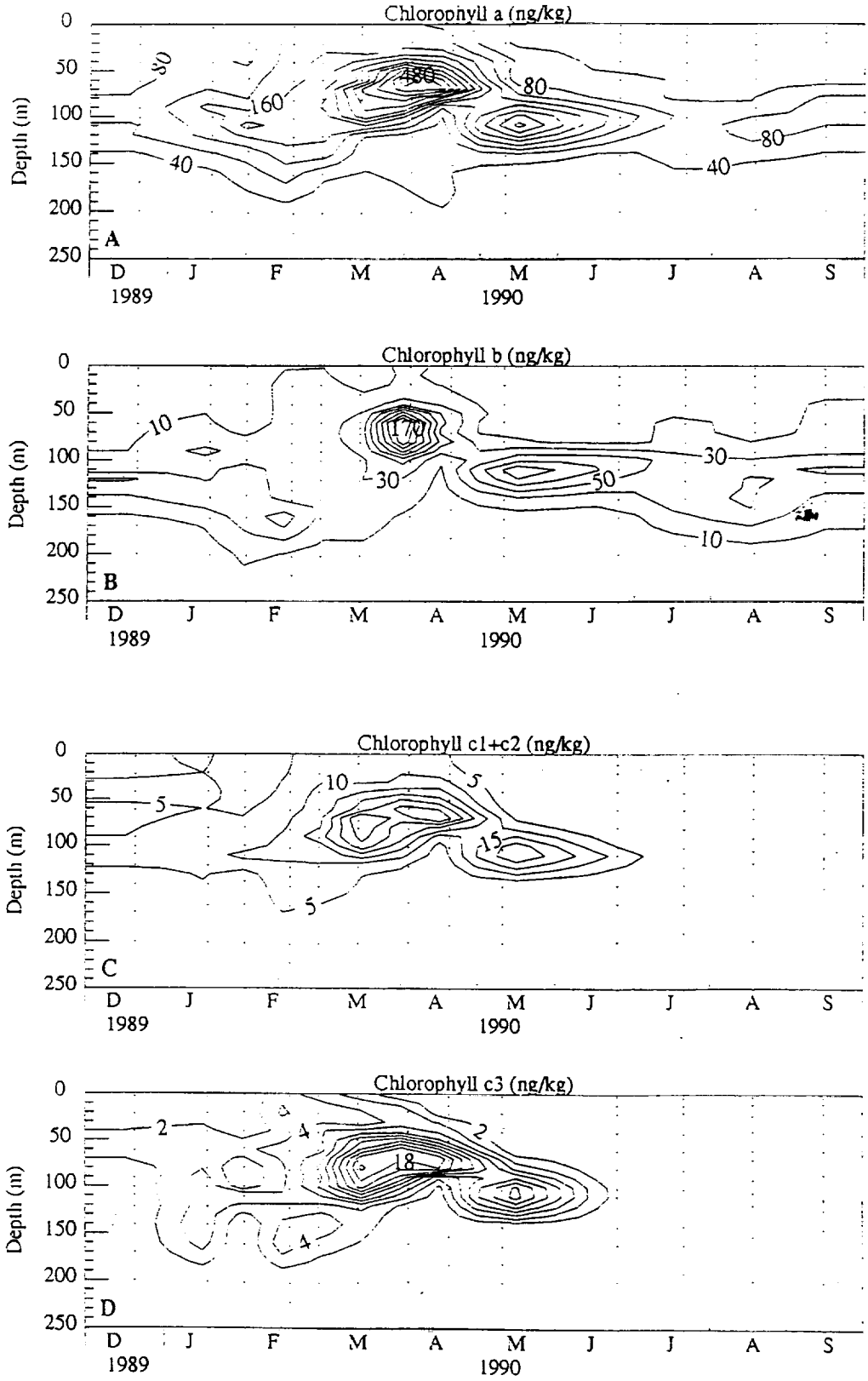
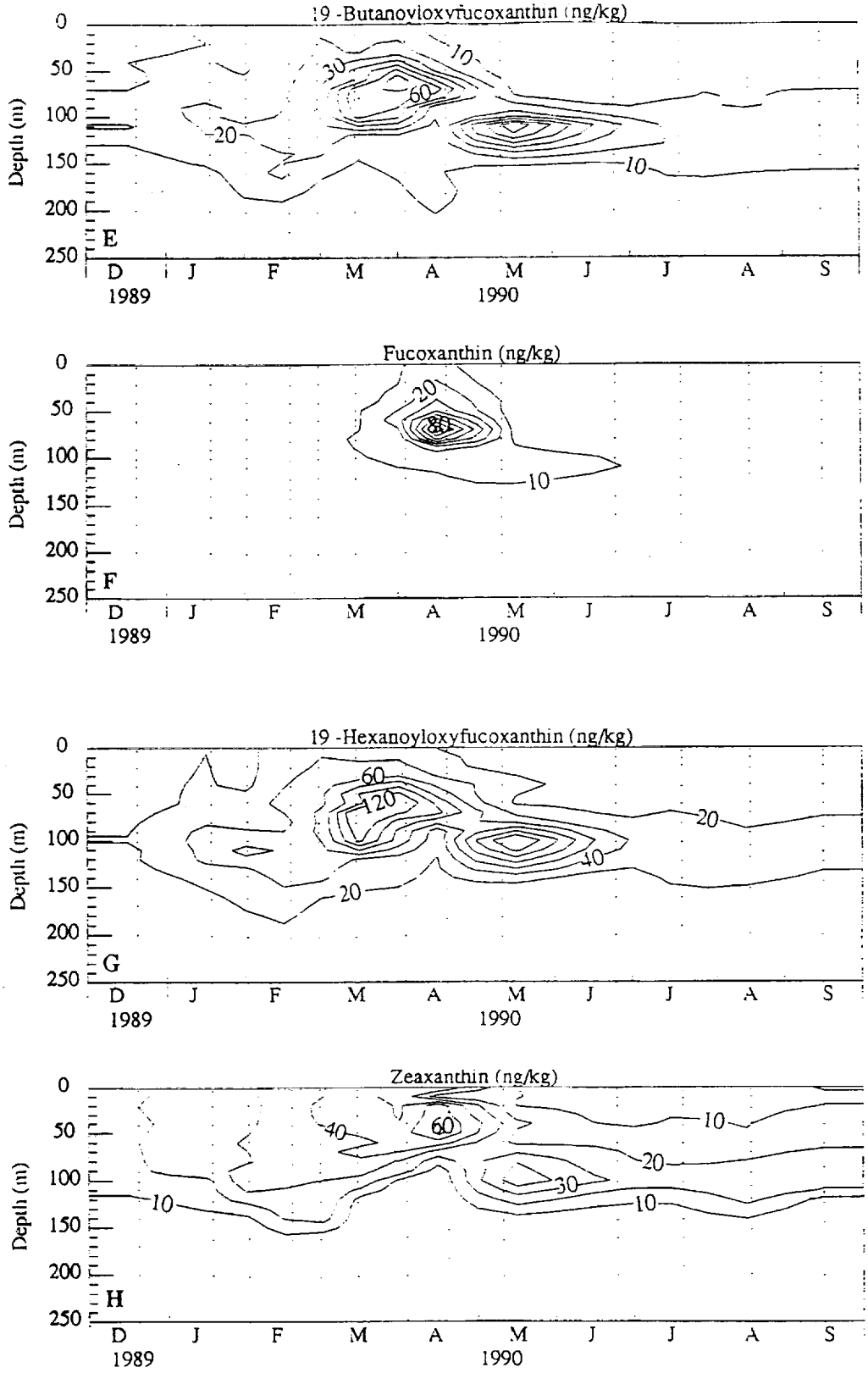
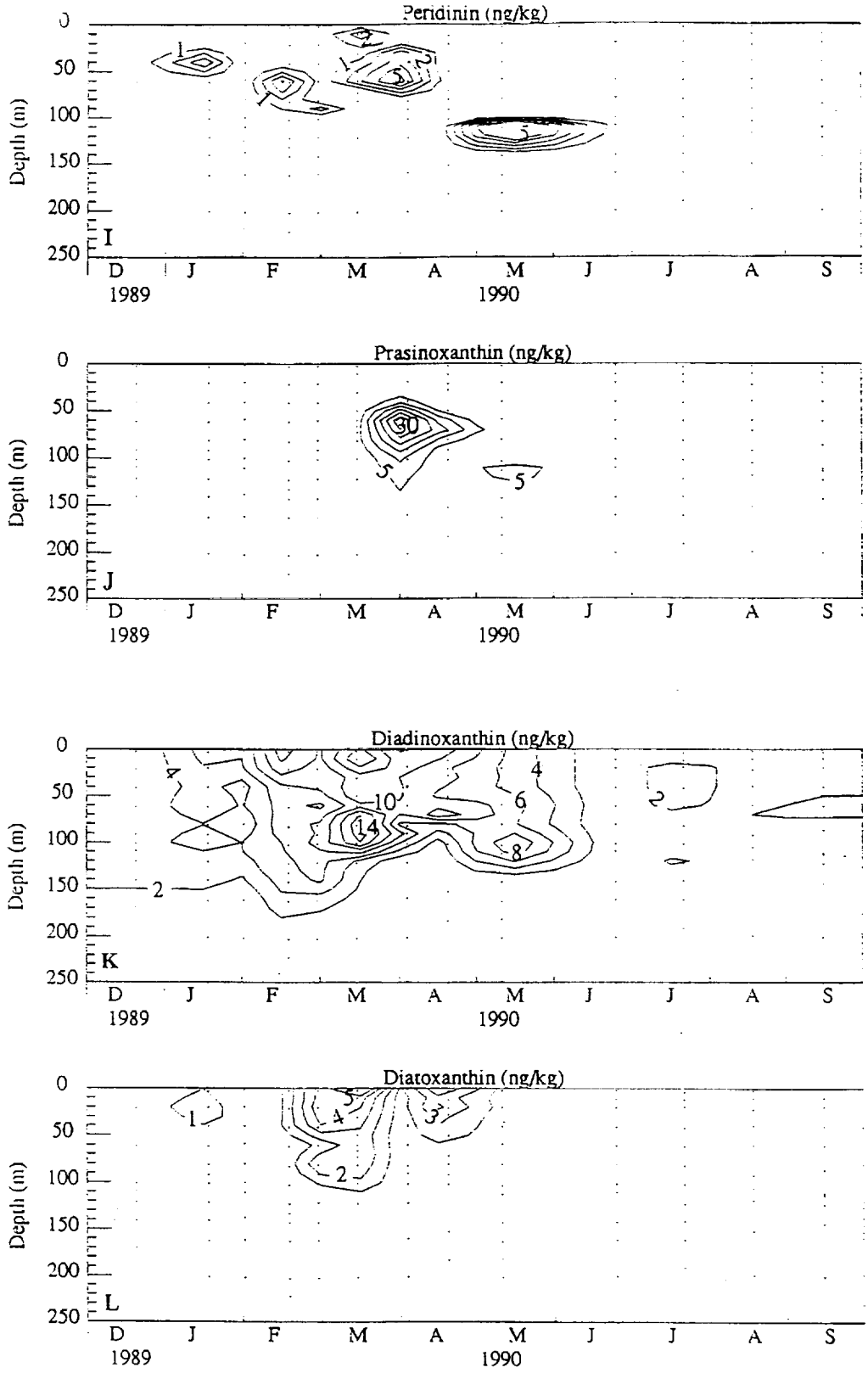


Figure 9. Contour plot of HPLC-determined pigment concentrations (ng L-1) at the BATS site during December 1989 - June 1990): (a) chlorophyll a; (b) chlorophyll b; (c) chlorophyll c1+2; (d) chlorophyll c3; (e) 19'-butanoyloxyfucoxanthin; (f) fucoxanthin; (g) 19'-hexanoyloxyfucoxanthin; (h) zeaxanthin; (i) peridinin; (j) prasinoxanthin; (k) diadinoxanthin; (l) diatoxanthin.


19 -Butanoyloxyfucoxanthin (ng/kg)
Depth (m)
0
50
100
150
200
250
E
D
J
F
M
A
M
J
J
A
S
1989
1990
30
10
60
20
10
Fucoxanthin (ng/kg)
F
20
80
10
19 -Hexanoyloxyfucoxanthin (ng/kg)
G
60
120
20
40
20
Zeaxanthin (ng/kg)
H
40
60
10
20
30
10
10


Peridinin (ng/kg)
Depth (m)
0
50
100
150
200
250
I
D
J
F
M
A
M
J
J
A
S
1989
1990
Prasinoxanthin (ng/kg)
90
5
5
J
Diadinoxanthin (ng/kg)
4
10
14
6
4
8
2
2
K
Diatoxanthin (ng/kg)
1
5
4
3
2
L

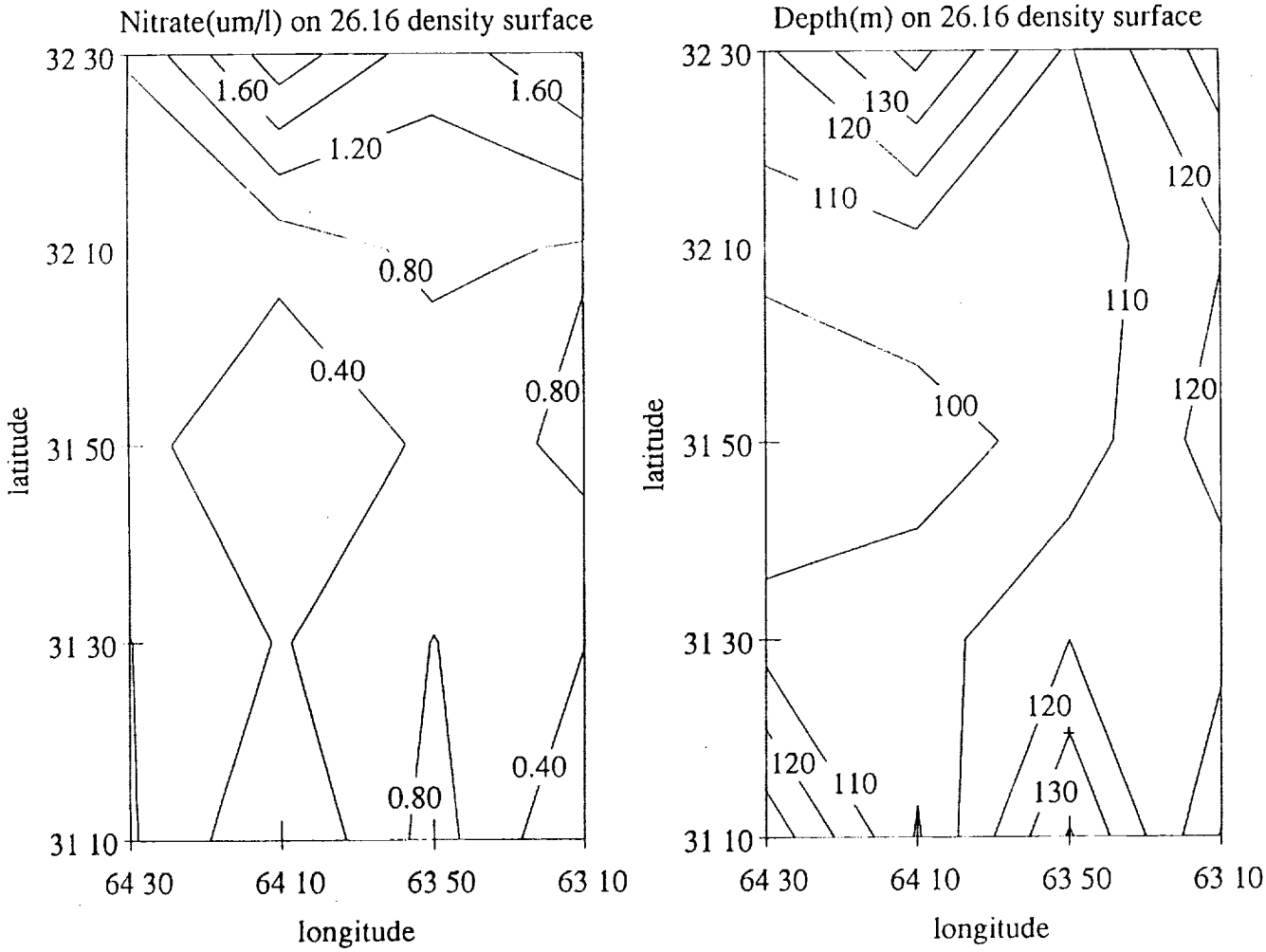


Figure 10. (a) Distribution of nitrate+nitrite on the 26.16 sigma-theta density surface over a 100 x 140 km area. (b) Depth of the 26.16 sigma-theta surface over the same area.

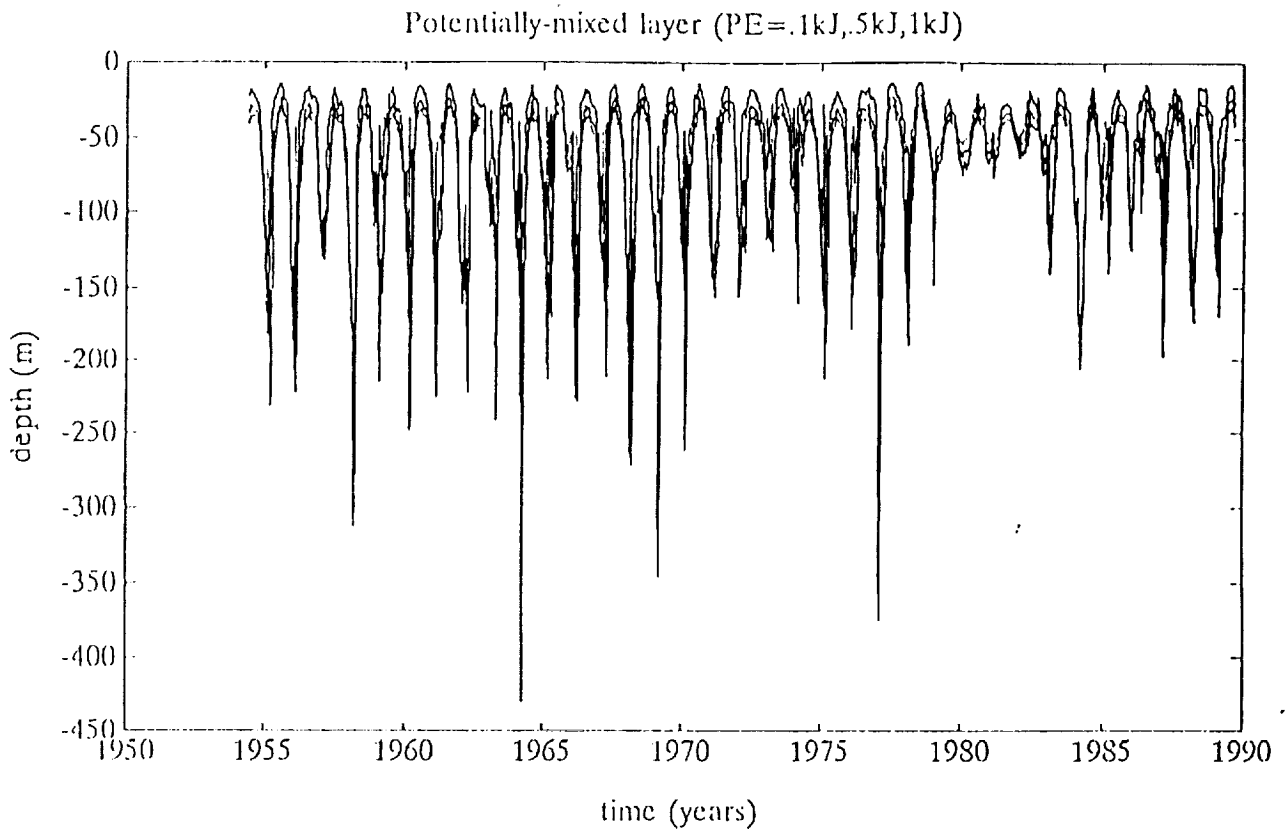


Figure 11. Depth of the mixed layer at Hydrostation S between 1954 and 1989. Mixed layer depth is calculated by integration of the potential energy of the density profile from the surface to values of 100, 500 and 1000 Joules.