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Foreword

As plans for the World Climate Research Programme(WCRP) began to evolve, it was evident that ocean studies, and oceanographers, were going to play an increasingly important role. To make improvements in the understanding of weather and in weather forecasting for the limited time horizon of two weeks or so, the principle objective of the Global Atmospheric Research Programme (GARP), meant that only the upper layer of the ocean and mixed layer dynamics were important. To understand climate, however, clearly called for a much more thorough understanding of a wide range of oceanic phenomena.

Meteorologists have traditionally called for a routine programme of ocean monitoring, analogous to the atmospheric World Weather Watch. This demand has been shared by some oceanographers, although the majority of the latter have been reluctant to see a large fraction of oceanographic resources devoted to this task, claiming that it is not a cost-effective use of a very limited capability. The call for an international programme of ocean monitoring in the interest of the World Climate Programme (WCP) has been made for several years at a succession of international meetings, governmental and non-governmental, including those of the Inter-governmental Oceanographic Commission (IOC) and the World Meteorological Organization (WMO).

In response, the Joint Organizing Committee (JOC) for GARP and the Scientific Committee on Oceanic Research (SCOR) called together a group of experts who met in Kiel in late 1978. That group concluded that the case for commencing a comprehensive programme was not yet sufficiently convincing to support an international appeal for participation. However, the group did recognize that an ocean monitoring programme would eventually be needed as an essential service in support of the WCP. The JOC/GARP and SCOR accepted the Kiel meeting's recommendation that a group be called together to propose a Pilot Ocean Monitoring Study (POMS). In September 1979 a POMS meeting was held in Miami, USA, just prior to the first meeting of the Committee on Climatic Changes and the Ocean (CCCO) which SCOR and IOC had established to deal with certain oceanographic aspects of the WCRP.

The POMS meeting recognized that eventual ocean monitoring would call for routine oceanic observations, and noted that many countries had, in fact, already carried out continuing programmes of routine observations for a variety of purposes. It was suggested that an examination of these time series, of the experiences in attempting to analyse them, and of the ways which data could be interpreted would provide very valuable insights for those designing ocean monitoring studies and programmes. Holding such a meeting could give an impetus for writing up and publishing results obtained from time series. Unlike research programmes, on-going time series do not usually provide particular stimulus to publish the results in anything but data reports. One of the recommendations of the POMS meeting was that the Joint SCOR/IOC CCCO and the JSC organize with the support of IOC and WMO a meeting on oceanic time series. They did so in Tokyo in May 1981 and charged the meeting with examining existing time series, their analysis and interpretation, and with making recommendations on future ocean monitoring programmes.

One of the conclusions of the Time Series Meeting was that:

« The nature of routine time-series measurements typically precludes collection by scientists who ultimately make use of these data. Technicians, ship's crews or other non-professionals are often engaged in the primary stages of data retrieval, editing and storage. The danger is that the quality and standards of these date, the desire to collect the data under adverse conditions in the field and the willingness of agencies or nations to continue the series may suffer if there is not sufficient encouragement to maintain them. There is, therefore, a real need to demonstrate the importance and usefulness of time-series data to understanding oceanic and atmospheric processes. »

In view of this, the Joint SCOR/IOC CCCO and JSC decided to prepare an annual review of the most recent data from the various on-going oceanographic time-series to encourage those collecting such data and to stimulate interest in them. This volume is the first issue of the Time Series Annual Review. It, and following volumes, will be issued by IOC and given wide distribution to facilitate the achievement of the stated objectives for their preparation.

The articles in Volume I look at time series from many aspects. Several are continuations of the articles originally presented in Tokyo in 1981 (See WCP-21, Time Series of Ocean Measurements, available from the Secretary, IOC) giving recent results. One takes another look at a 1950-1953 data set after 30 years of steady progress in understanding the uses of such data sets. The articles deal with time series at single locations, over ocean basins, along extended and short tracks and one describes a long-term model hindcast of the large-scale circulation and the need for long-time series of ocean current data. It is the intention of the editors to include such a variety of articles in future volumes as we believe this clearly demonstrates the wide use and importance of time series of ocean measurements in climate studies. In publishing this time series annual review, the objective of the IOC is to facilitate, through the concerted action of its Member States, the acquisition of data and exchange of information in a field of study of great interest to the world community. This publication also represents part of the support provided by the Commission as an inter-governmental body responsible for the oceanographic aspects of the World Climate Programme, as decided by the IOC Assembly at its Eleventh Session (Resolution XI-3).

Lastly, should you be interested in having an article published in this annual review, you are invited to submit an abstract to the Secretary, Intergovernmental Oceanographic Commission, Unesco, 7 place de Fontenoy, 75007 Paris, France.

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1. CalCOFI a 33-year oceanographic survey of the southern California Current System

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Long time series are essential for statistical examination of climatic variability in the ocean in order to observe repeated realizations of the climatic signal. The 1982-3 El Nino warming event in the tropical Pacific has demonstrated how cautiously conclusions drawn from limited data records must be interpreted. This El Niño differs in a number of respects from composite pictures of the "typical" El Nino derived from the previous 30 years of data (see Philander, 1983, for a discussion). One of the roles of the Committee on Climatic Changes and the Ocean (CCCO) is to stress the importance of continuing existing long time series and establish new ones in order to better understand these climatic signals. An important element of this function is to study existing series not only for information they contain on climatic variability in the ocean but also to identify weaknesses and limitations that might be avoided in newly established measurement programs.

The 33-year physical and biological survey of the southern California Current System (CCS) by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) is probably the most extensive "open ocean" sampling program in existence. The purposes of this brief chapter are to: (1) describe the CalCOFI sampling strategy; (2) summarize scientific results relevant to ocean climatic variability; and (3) discuss weaknesses of the CalCOFI sampling strategy.

The goal of CalCOFI is to study the underlying principles governing behavior, availability and total abundance of the major pelagic fish stocks in the southern CCS. A number of physical and biological quantities have been measured routinely since 1949 as part of a detailed study of the ecology of this region. The spatial domain covered most extensively by CalCOFI is shown in Fig.1.1. An important feature of the sampling strategy for analysis of the data is that a geographically fixed 65 km station grid (somewhat tighter grid spacing nearshore) was established in 1950 and maintained throughout the 33-year program.

Temporal sampling of this station grid was intended to be monthly but has been somewhat erratic due to financial constraints. Not all stations in the grid were occupied during any particular sample month. The 150 grid points in Fig. 1.1 correspond to stations occupied ≧ 40 times between 1950 and 1979. From 1950 to 1960, monthly cruises were conducted with few interruptions. Financial problems forced a reduction to quasi-quarterly cruises (nominally January, April, July and October) in 1961. This sampling strategy was maintained through 1968, after which CalCOFI changed to monthly cruises every third year (1969, 1972, 1975, 1978 and 1981) due to difficulties with ship scheduling. Typically, 40 % of the 150 stations shown in Fig. 1.1 were occupied during a CalCOFI sample month.

The wealth of data collected by CalCOFI can be used to study physical and biological variability over a wide range of space and time scales. The discussion here will be limited to those scales most appropriate for climate studies, i.e. only the very large spatial scales (≧ 100 km) and interannual time scales.

The most extensive of the biological measurements made by CalCOFI are the macrozooplankton net tows.The large-scale aspects of zooplankton variability have been examined by Bernal and McGowan (1981) and Chelton *et al.* (1982). Time series of nonseasonal zooplankton for the four areas in Fig. 1.1 are shown in Fig. 1.2. (The long-term seasonal average values for each calendar month have been removed from the raw measurements.) It is evident that there are substantial year-to-year variations in zooplankton biomass that are highly coherent over all four regions.

Examination of time series of nonseasonal physical variability in the southern CCS shows that these large-scale biological variations are closely coupled to climatic variations in the California Current (Fig. 1.3). Fig. 1.3a is the average of the four individual zooplankton time series shown in Fig. 1.2. The average 10 m temperature and salinity over the 150 grid points in Fig. 1.1 are shown in Figs. 1.3b and c, respectively. The salinity signal is somewhat noisy but zooplankton biomass and temperature are highly correlated.

These large-scale environmental and biological changes are related to nonseasonal changes in the equatorward transport of the California Current. An index of this transport is shown in Fig. 1.3d (see Chelton *et al.* 1982 for details). During periods of abnormally strong equatorward flow the water temperature drops and zooplankton biomass is anomalously high. It is hypothesized that these zooplankton variations reflect a response to variations in phytoplankton biomass resulting from changes in the supply of nutrients advected southward from high latitudes.

The causes of these climatic changes in the California Current have not been fully determined. It is known that they are not locally generated by the wind field in this region. They are, however, significantly correlated with coastal sea level along the California coast which is, in turn, correlated with El

Figure 1.1 Grid of CalCOFI stations occupied 40 or more times between 1950 and 1979. Boxes represent the four areas for which monthly averaged zooplankton has been computed and n̄ is the average number of macrozooplankton net tows per month for each area.

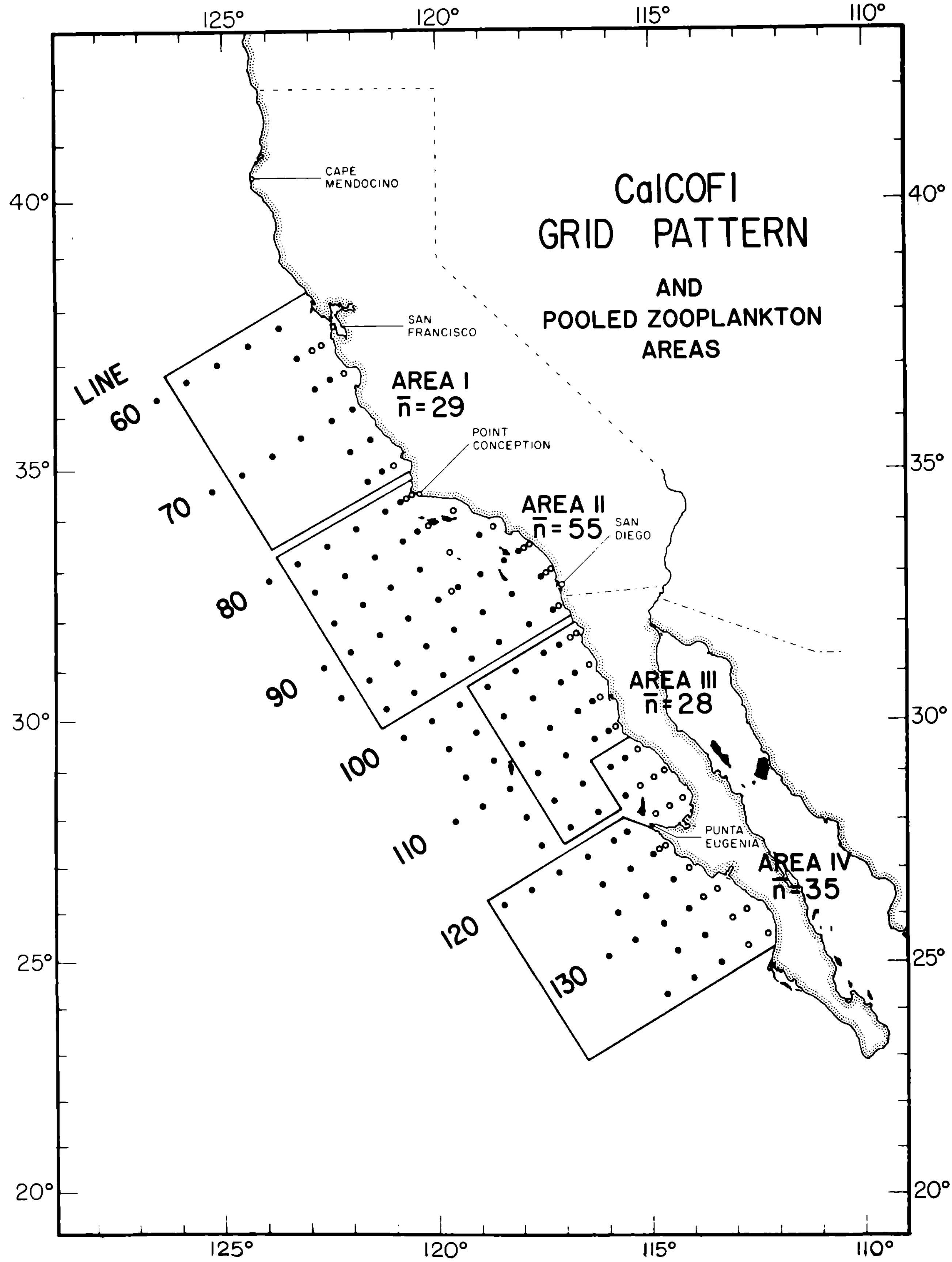


Figure 1.2 Low-pass filtered time series of nonseasonal zooplankton volume in loge (10^{-3} ml/m^3) for the four areas shown in Fig. 1.1.

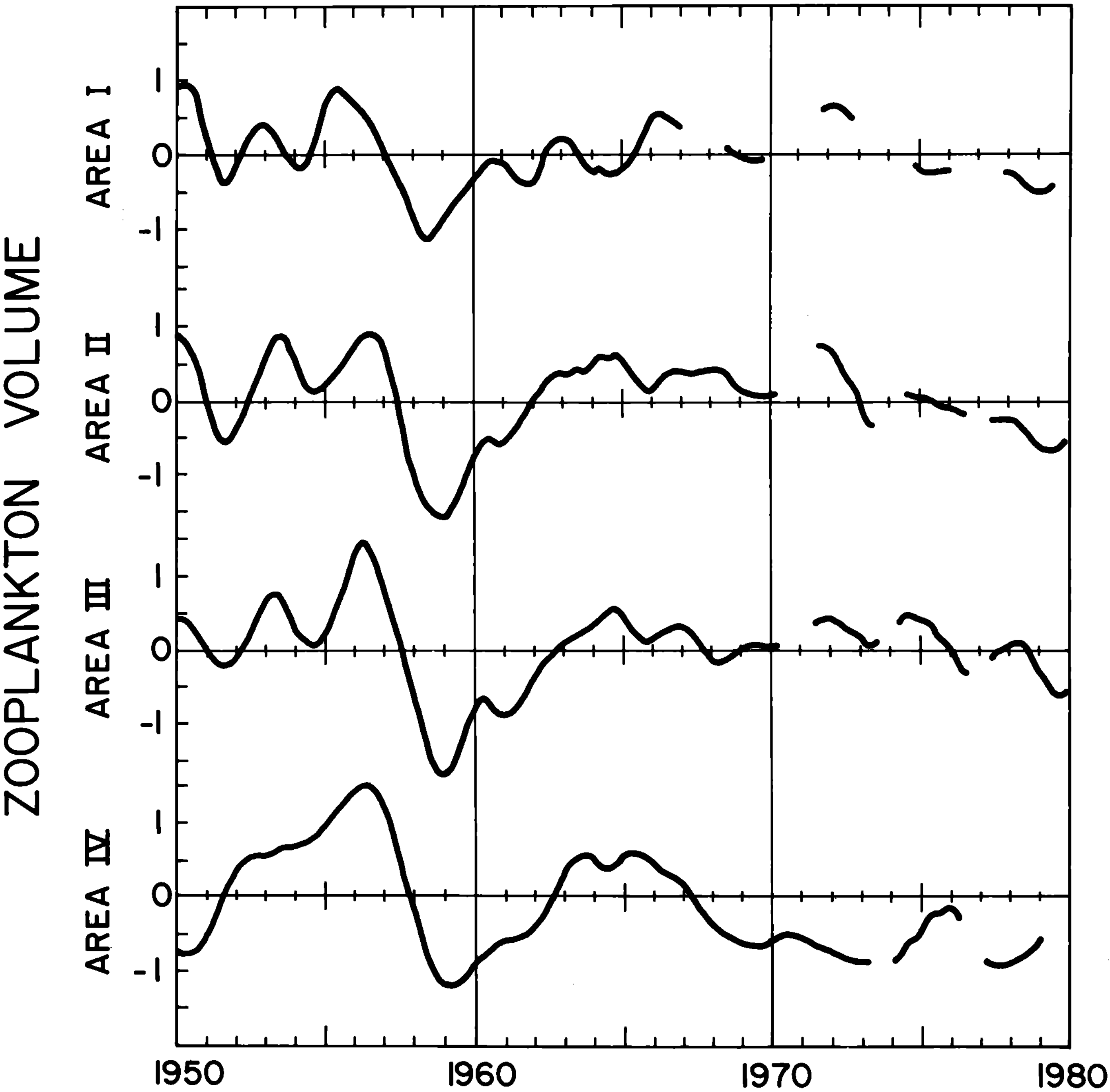
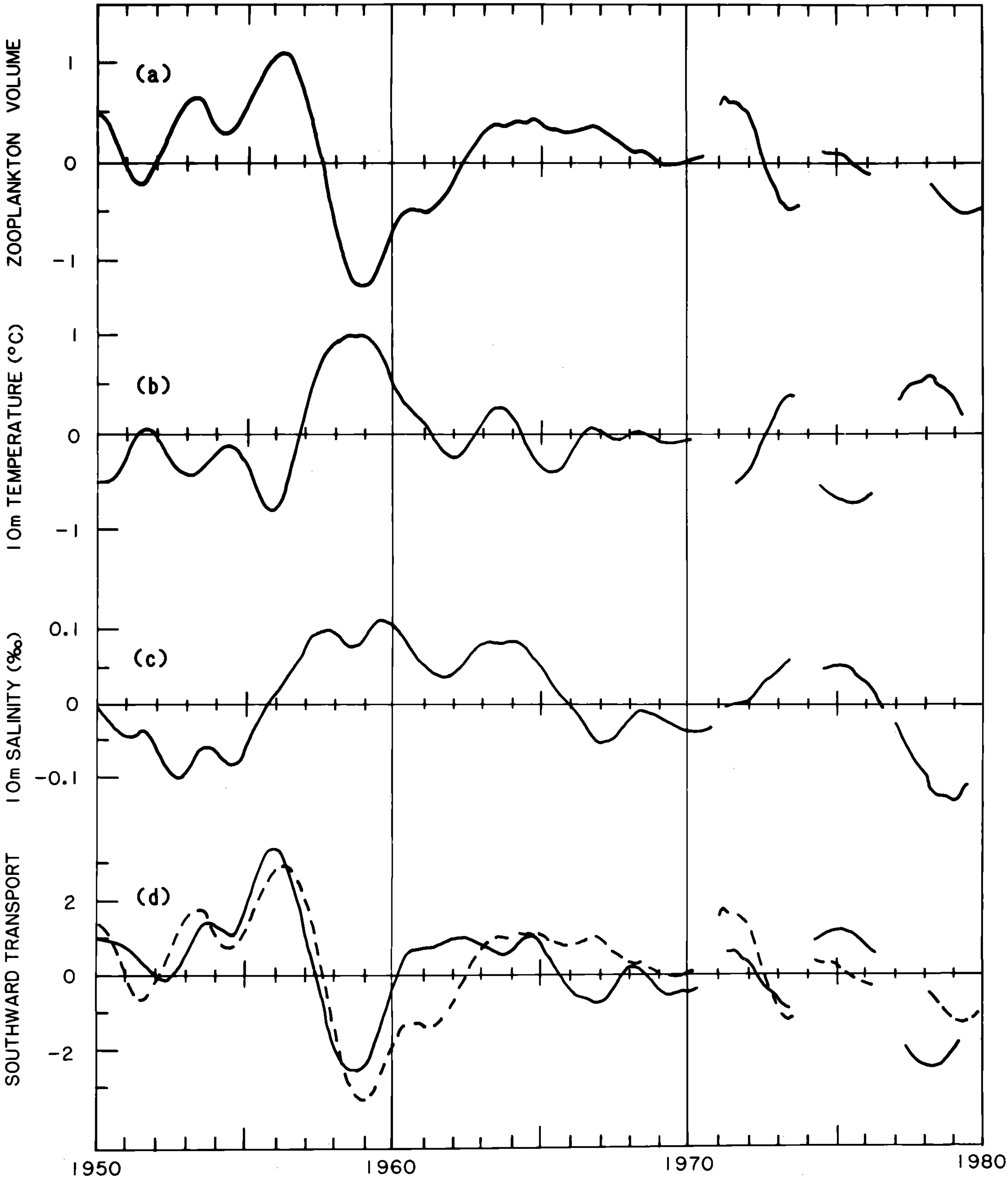


Figure 1.3 Low-pass filtered time series of: (a) the average of the four zooplankton time series in Fig. 1.2; (b) the average 10 m temperature in °C over the 150 stations in Fig. 1.1; (c) the average 10 m salinity in ‰ over the 150 stations in Fig. 1.1; (d) an index of southward advection (see Chelton *et al.*, 1983). Dashed line in (d) represents zooplankton time series in a).



Niño occurrences in the tropical Pacific. Enfield and Allen (1980) and Chelton and Davis (1982) have presented evidence for poleward wave-like propagation of this El Niño signal.

It should be stressed that there are significant discrepencies between the large-scale variations in the CCS and this simple model of poleward propagation. Longer time series are necesary to determine the detailed nature of the causes of this large-scale variability.

The most serious limitation of the CalCOFI data set is the present three-year sampling interval. The most recent CalCOFI year was 1981 and the next will not be until 1984. Thus the 1982-83 warming event in the California Current apparently related to the tropical Pacific El Nino is entirely missed. The usefulness of CalCOFI data for studies of climatic variability in the southern CCS has effectively been greatly reduced since 1969.

Incomplete sampling of the grid in Fig. 1.1 is also somewhat of a problem. Objective analysis techniques are required for statistical examination of the dominant temporal and spatial signals in the data (see Chelton *et al.* 1982 for a discussion). These techniques are only possible because the program has been maintained for a large number of years. It would be impossible to determine accurately the statistical relationships required for objective analysis from short records of only a few years.

In retrospect, the full grid pattern in Fig. 1.1 could be significantly reduced with a resulting saving in time and money and little loss of information for studies of climatic variability in the CCS. This fact can only be ascertained, however, after a number of years of "oversampling" of the grid pattern from which the dominant spatial scales could be statistically determined.

It is universally agreed that the three-year sampling strategy is undesirable. CalCOFI is presently considering alternative strategies. The plan that will most probably be adopted is a change to quarterly cruises without any increase in total funding. This will probably require a reduction in the number of grid points occupied during each quarterly cruise. The selection of stations to be omitted is presently being investigated under conflicting requirements to measure the large-scale climatic signal but also to resolve the size and distribution of fish populations.

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2. Abidjan Coastal Hydrostation, 1966-80*

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*This chapter has been taken from *Archives Scientifiques, Centre de Recherches Océanographiques, Abidjan*, vol. VII, no. 4, November 1981, pp. 1-28, published under the sponsorship of the Ministère de la Recherche Scientifique of the Republic of the Ivory Coast. Those wishing to obtain copies of the full set of figures (15) and tables (19) produced using the 1966-80 data, and information on data collected since 1980, may write to the Centre de Recherches Océanographiques, 10 B.P. V18, Abidjan 01, République de Côte d'Ivoire.

For more than fifteen years the Oceanographic Research Center has maintained a coastal station off Abidjan. This station is situated in 43 metres of water at 51°13'N, 4°03'W. Until January 1977 the station was situated in 30 metres of water at 15°13'N and 4°02'W.

The observations started on 29 March 1966. The ships *Licorne* and *Reine Pokou* were responsible for the majority of the stations from March 1966 to January 1975. Occasionally the station data were obtained using other vessels: *Vigilant* in 1970; the *N.O. Capricorne* in 1972, 1973 and 1975 and *Coriphene II* in 1973. The trawlers *Eloka* and *Carnot* carried out the operation of the station from 12 December 1973 to 10 October 1974 and from 14 October 1974 to 6 February 1975. The observations at the hydrostation are made while the ship is at anchor or kept on location using a marker buoy. From March 1966 to the end of December 1976, there were five observational levels: 0, 5, 10, 15 and 20 metres. From January 1977 to mid-July 1981, the following routine measurements were made:

(1) Current speed (centimetres per second)
(2) Wind speed (metres per second) and direction
(3) Transparency (Secchi disk)
(4) Temperature and salinity at depths of 0, 5, 10, 15, 20 and 25 metres
(5) Vertical distribution of plankton between the surface and 35 metres

The hydrostation maintained at Abidjan permits, amongst other things, the study of the seasonal variability of the thermal structure. We have prepared temperature-salinity (T-S) diagrams for each month and calculated the dynamic height for each station.

Temperature and salinity variations control, to a large extent, the biological conditions of the marine environment. The T-S diagrams characterize the water masses of the region.

T-S diagrams were prepared month by month with the aid of fifteen-day temperature and salinity means at depths of 0, 5, 10, 15, 20 and 25 metres. For the fifteen years studied, the observations from January to April are closely grouped. In May a certain dispersion is observed, apparently connected with the beginning of the rainy season. By contrast, in August and September the dispersion is weak (the dry season and upwelling). The T-S diagrams for January and July are shown as Figs. 2.1 and 2.2.

For each hydrostation we have five to six T-S couples corresponding to the different levels of measurement. From each one of the couples we determined, with the aid of oceanographic tables, the quantities σt, Δst, σtp, σsp.

We have utilized here the tables of Kalle and Thorade (1940) and the tables of Lafond (1951); the dynamic height anomaly (D) is expressed in dynamic centimetres. Five tables (see as an example Table 2.1) give the dynamic height with the dates of execution at all of the stations from 1966 to 1980. Similarly three figures (see as example Fig. 2.3a) present the annual variations of dynamic height anomalies at the coastal station. In addition, we have calculated the 15-day means (D_{15}) of the dynamic height anomaly and their deviations and the monthly means (D_{30}) and their deviations. These have permitted us to construct "model-years" (see Fig. 2.3.b, c). The precision of the measurements is indicated on the curve by the respective deviations.

Figure 2.1 T-S diagram and regression lines, January 1967-January 1981, Abidjan Hydrostation (0, 5, 10, 15, 20, 25 m). AMR: major reduction axis; T: regression of T into S; S: regression of S into T; correlation coefficient r = - 0.86.

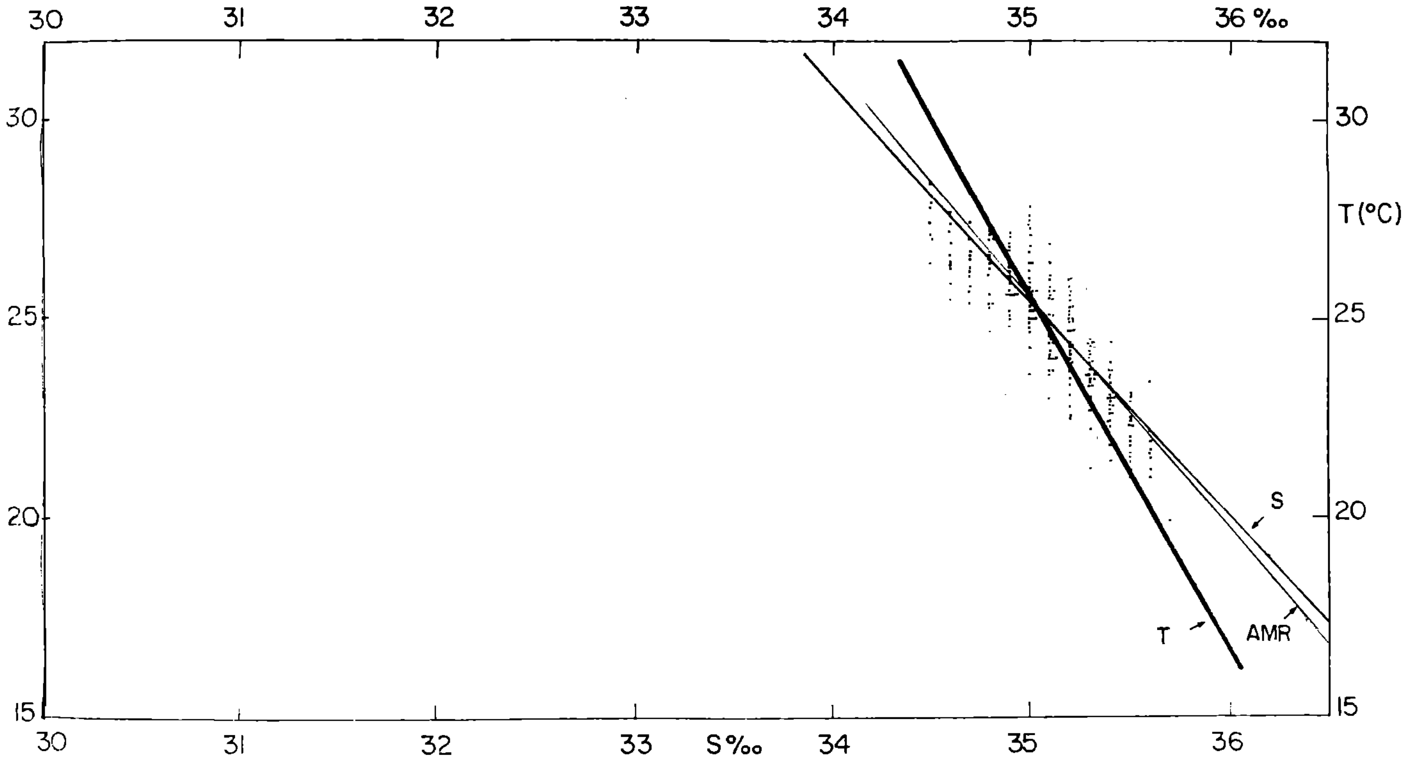

Figure 2.2 T-S diagram and regression lines, July 1966-July 1981, Abidjan Hydrostation (0, 5, 10, 15, 20, 25 m). Abbreviations as in Fig. 2.1. Correlation coefficient r = — 0.75.

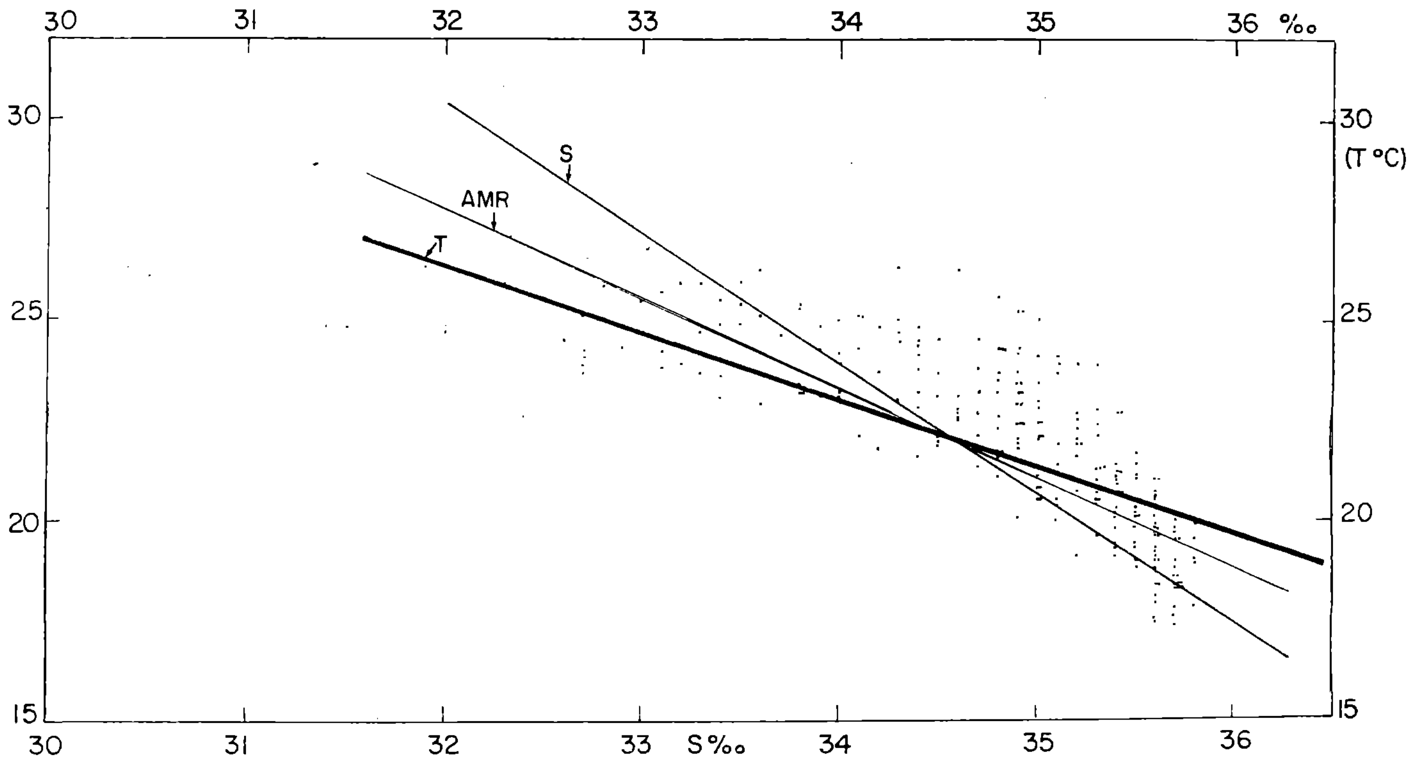

Figure 2.3a Annual variations of dynamic height anomalies at the Abidjan Hydrostation, 1978-80.

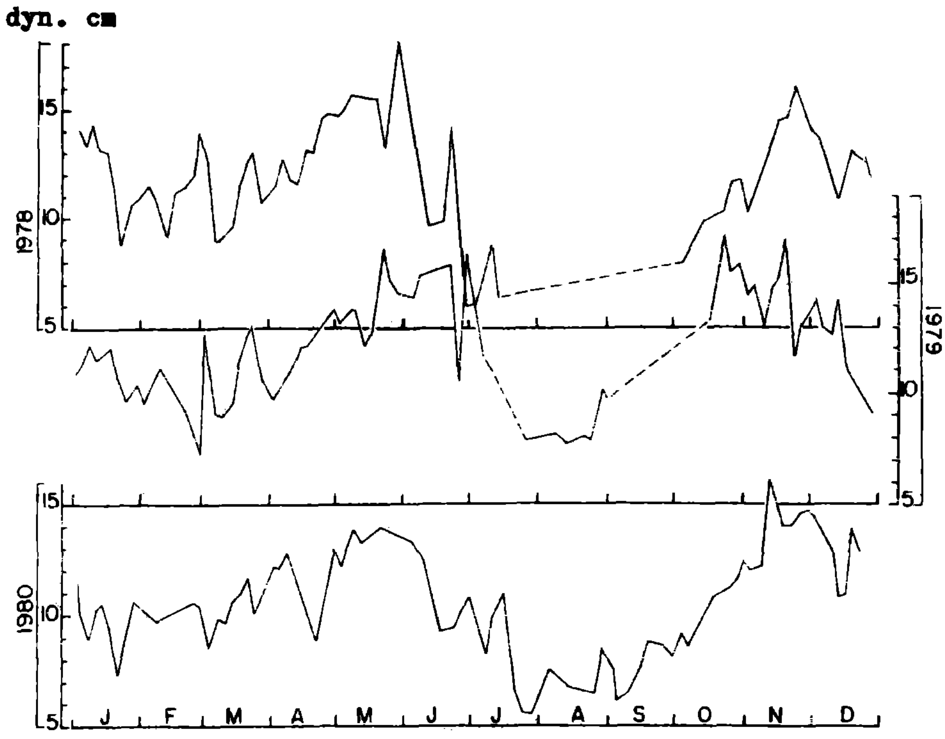

Figure 2.3b Model year from 15-day means, 1966-80 $\bar{D}_{15}$ relative to 20 dB in dyn. cm.

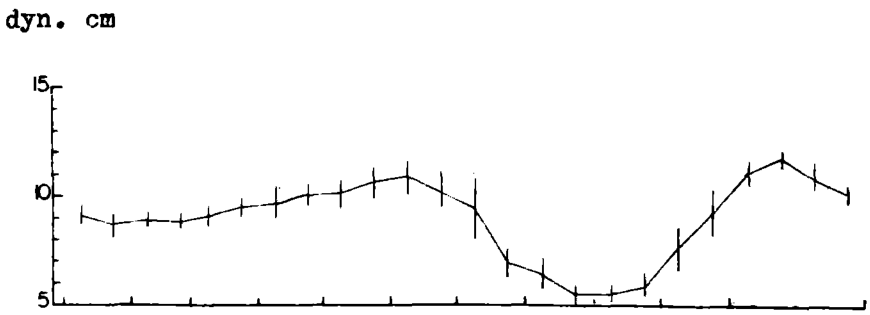

Figure 2.3c Model year from 30-day means, 1966-80 $\bar{D}_{30}$ relative to 20 dB in dyn. cm.

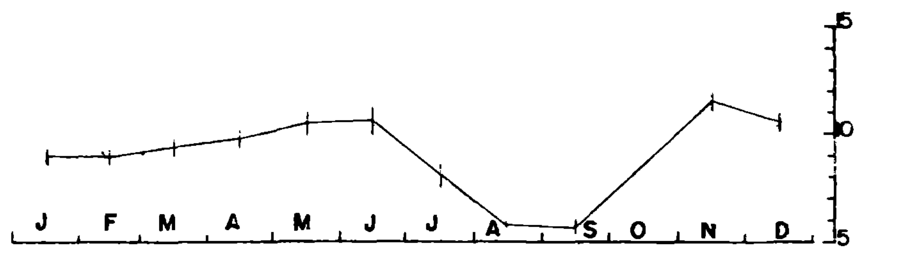

Table 2.1 Dynamic heights in dynamic centimetres
D relative to 20 dB in dyn. cm.

Month

	J	F	M	A	M	J	J	A	S	O	N	D
1				7,39								11.90
2		9,61			8,54	12,26		4,80				
3	7,88		8,83								11,23	
4				9,26			13,34		4,83			
5					8,78			4,65				11,22
6	9,36					12,92					11,86	
7			8,87	9,59			12,36		5,43	5,51	11,73	
8		8,87									12,14	9,62
9								3,63				
10	9,96				9,52	13,51				4,49		
11		8,09	8,34				10,10					
12	9,57			10,07	10,22			4,90	4,61			9,89
13						11,55	9,32			6,11		
14		7,86	8,05	10,09							12,47	
15			8,52						5,30			9,27
16					10,67							
17		8,68	8,88					5,26		5,69	11,68	
18	7,92						7,80		5,88			
19				10,19								8,70
20					10,44	12,34				7,13		
21	8,71	9,15	9,07	10,59			7,24				10,83	9,70
22								5,16	4,77			
23					10,98	11,31						8,47
24	6,36	9,63									11,32	
25			7,47	10,45						7,32		
26	5,76	9,38			11,52			4,43	5,37			9,78
27						12,61				8,04		
28		7,64	7,31	9,27			5,17					
29									5,16		12,03	11,02
30						14,04		4,63		9,05		
31	8,94				11,35							

3. Thermal variations on the Equator in the eastern Pacific

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Since 1974, the Centre ORSTOM de Noumea has operated a surface temperature and salinity survey along the shipping route between Tahiti and Panama. Due to an agreement between France and the United States, this experiment was supplemented in 1979 by an expendable bathythermograph (XBT) survey recording subsurface (0-475 m) temperatures. Some results have already been published (Donguy and Hénin, 1980; 1981).

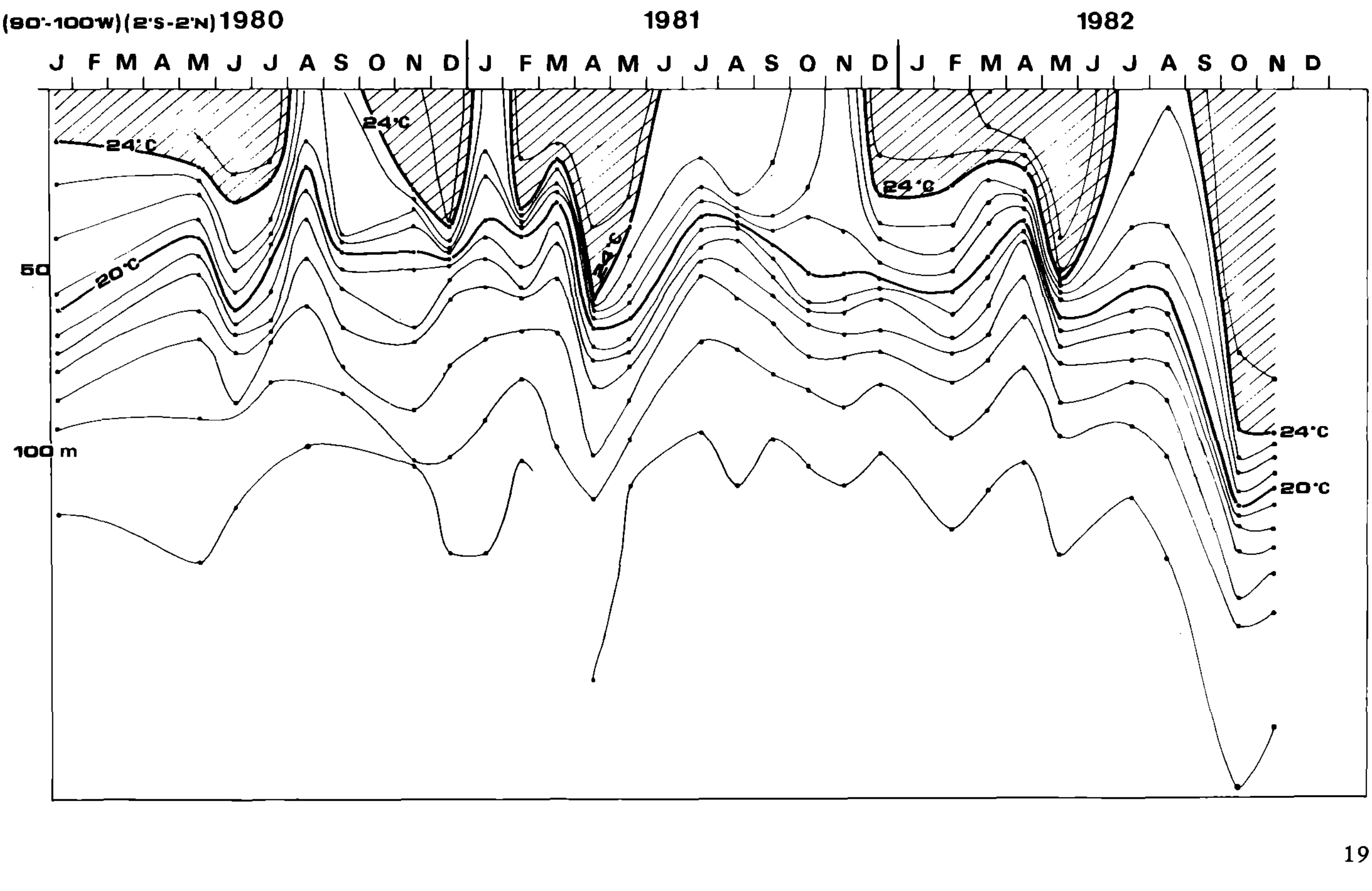
The equatorial area between Tahiti and Panama is most sensitive to climatic influences. It is subject to seasonal variations connected with the wind field and also to low-frequency variations connected with the Southern Oscillation and El Niño. The equatorial area under consideration here lies between longitudes 90° and 100°W and latitude 2°N and 2°S. Subsurface temperature from XBTs has been averaged by month in this area for the years 1980, 1981 and 1982 (see Fig. 3.1).

Up to August 1982, seasonal variations may be defined. During the first part of the year the temperature is more than 24°C from the surface to at least 20 meters depth and at most 50 meters depth. This warm season lasted from January to July in 1980, from February to June in 1981 and from December 1981 to July 1982, and is due to the absence of, or to the decrease in, the equatorial upwelling. The change in intensity of equatorial upwelling may be connected to the wind speed; usually, during the first part of the year the wind speed is less than 10 knots (Donguy and Hénin, 1980).

Conversely, the cold season usually occurs during the second part of the year and is probably due to stronger equatorial upwelling induced by a wind speed of more than 10 knots. However, in recent years, a well-defined cold season appeared only in 1981, from July to December. In 1980, warm water with temperatures of more than 24°C occurred between October and December; and in 1982, starting in September, a strong warm anomaly of the El Niño type appeared.

In September 1982, the warm water (> 24°C) extended from the surface to a depth of 100 m.

Figure 3.1 Eastern Pacific equatorial surface layer temperature (°C), January 1980-November 1982.



Winds recorded simultaneously with the XBT measurements on the equator were from the South and consequently could not sustain equatorial upwelling. This warm anomaly resembles a major El Niño, such as the one in 1972. However, it is out of phase relative to the usual El Niño which starts, as is implied by the name, at Christmas-time.

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4. Some monitoring results from west of Britain

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Salinity and temperature

The clearest signal of change in Northeast Atlantic waters in recent years has been the sharp fall, then rise, in salinity during the 1970s. Although, for instance, in the Rockall Channel this amounted to a *maximum* change of about 0.12 x 10^{-3} over six years, this was sufficiently unusual in a region of generally small variations to have become known in European hydrographic circles as the "great" 1970s salinity anomaly, and its appearance at various locations is being studied by a number of workers. The immediate cause of the freshening appears to have been in the increasing amount of Subarctic Intermediate water reaching the southern entrance to the Rockall Channel from the western side of the oceanic polar front, partly because the front was displaced eastwards during the early 1970s. Fig. 4.1 shows the location from which the time series of Fig. 4.2 is drawn. The latter consists of anomalies from 1961-70 means of temperature and salinity for surface observations taken during January to March of each year, the season when surface data provide a good indication of conditions in the upper 300 m or more of the water column, due to the deep winter mixing that occurs. Most of the observations were collected by UK Weather Ships on passage to and from their stations, on behalf of the Fisheries Laboratory, Lowestoft. The salinity minimum of this series can be seen to have occurred in the winter of 1976; and examined against archived data for 1905 to 1936 (see World Climate Programme Report WCP21, pp. 245-54), the two major features of the series since the beginning of the century are a high salinity period centred upon 1930 and the low salinity of the 1970s. Although monthly surface values during the remaining nine months of the year have less relevance to long-term changes due to summer stratification, and are also biased in the case of temperature by irregular dates of sampling during months of rapid warming and cooling, means by decades emphasize the changes of the past thirty years. Fig. 4.3 shows the warm character of the 1950s, the cooler but still saline 1960s and the slightly colder but much less saline 1970s. The winter salinity anomalies of Fig. 4.2 rise rather steadily from 1977 onwards, but monthly values, smoothed by a three-month running mean in Fig. 4.4, suggest that in most years between 1974 and 1980 the greatest changes arrived in the surface layer in the autumn, with their effects upon the main body of Rockall Channel water appearing damped by the subsequent deep winter mixing.

Current measurements in the deeper water

Since 1978 moored current meters have been deployed in the Rockall Channel at sites F and M shown in Fig. 4.1. The channel is at its narrowest here, and the deep (ca. 2000 M) water is further restricted by Anton Dohrn seamount which rises to 530 m depth in the centre of the channel. From geostrophic sections it would be expected that the main northeastward flow of Atlantic water towards the Norwegian Sea would pass to the west of the seamount, in the vicinity of mooring F, with a weaker southerly flow at M. Whilst the latter statement is broadly confirmed by the current measurements at M, those at F show considerable variation from month to month and year to year. As an example, Fig. 4.5 shows a hodograph of monthly vectors at F during 1981-2. Water movements at both stations are notably coherent throughout the water column and a seasonal signal penetrates to the lower depths in the manner shown by Dickson *et al.* (*Nature*, vol. 295, pp. 193-8). Residual movements are typically 200 to 500 km/month at depths of 100-200 m, but wide variations in direction of flow mean that residual drifts over a year are frequently of the same order. Because of gaps in the data due to the interruption of mooring operations by bad weather, lost moorings, and similar problems, it is difficult to offer simple indices of annual movements, but Table 4.1 gives a crude analysis of the data in terms of overall northerly and southerly components during the calendar months part-months for which observations exist. The general predominance of southerly movements at M can be seen, but at F the emphasis changes from northerly residuals in 1978 and 1979 to southerly ones in 1982. During some periods examination of the records suggests the passage of mesoscale eddies past the moorings.

Current measurements at the continental slope

Moorings have been operated for limited periods at two locations on the continental slope west of Britain, moorings P and L1 (Fig. 4.1). In contrast to the deeper moorings, at P in a sounding of 1000 m currents are particularly steady in direction, with a northerly flow averaging 14.5 km/day at 90 m depth during May-September 1979 and 10.8 km/day at the same depth during May-September 1982. Fig. 4.5 includes a hodograph for the latter deployment. The steady northerly currents persisted to

Figure 4.1 Location of SMBA current meter moorings and area (outlined) to which the temperature and salinity observations refer.

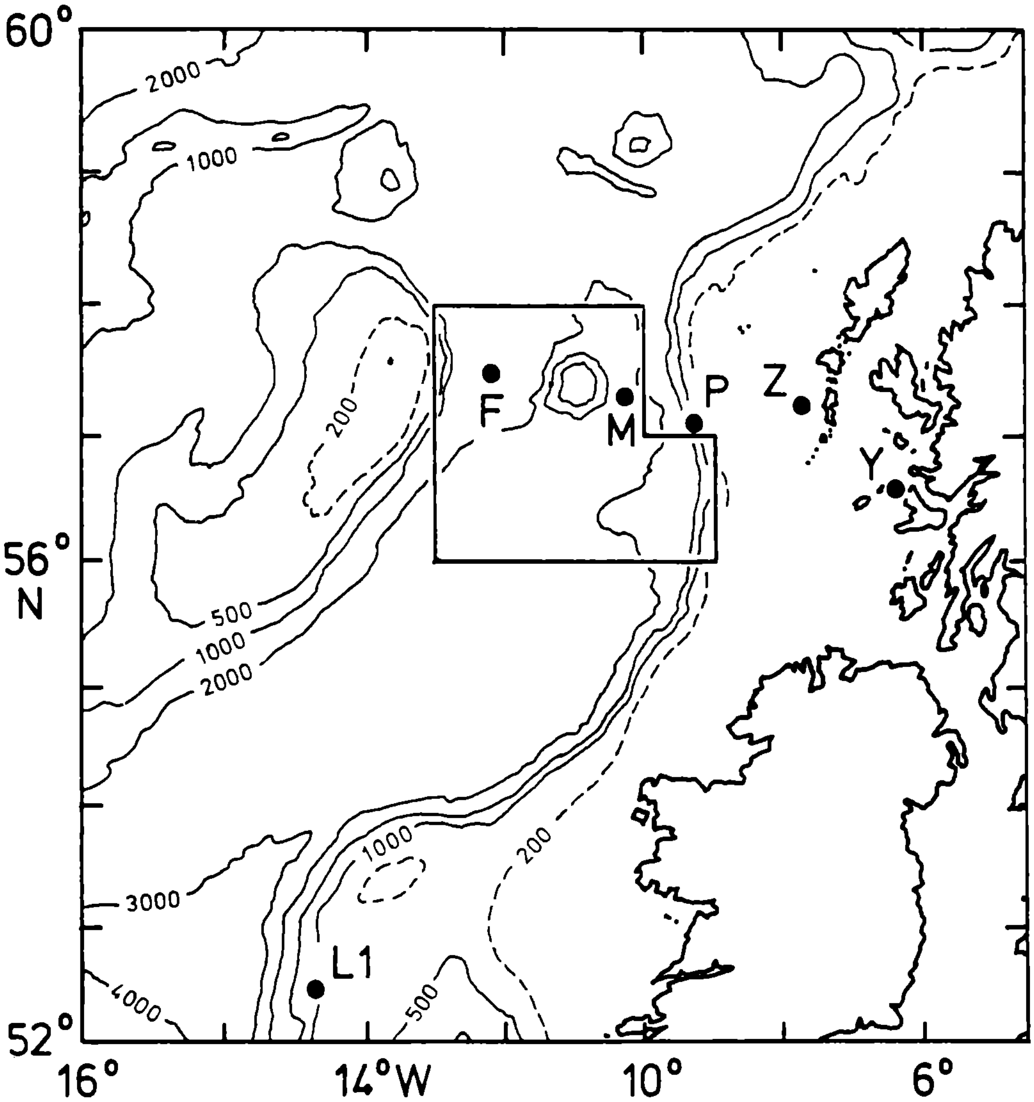

Figure 4.2 Winter anomalies, from 1961-70 means, of surface temperature and salinity in the central Rockall Channel.

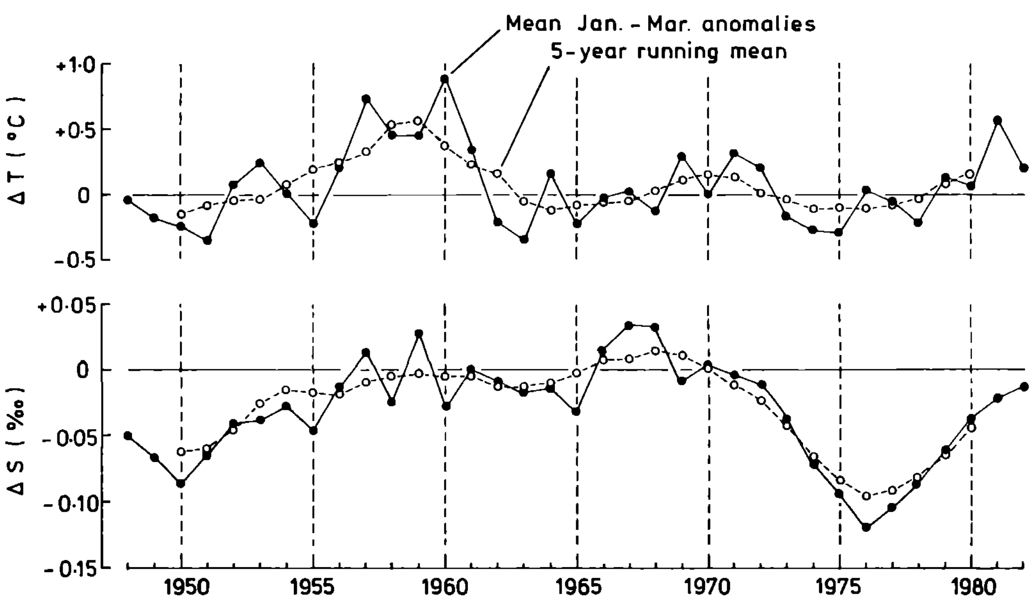

Figure 4.3 Montly means of surface temperature and salinity in the central Rockall Channel for three decades.

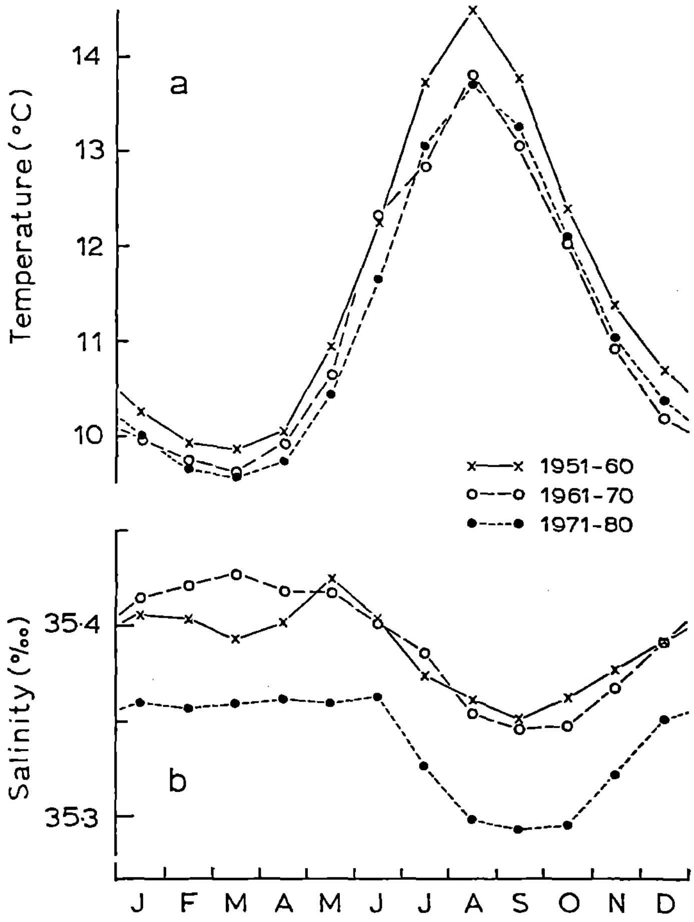

Figure 4.4 Monthly salinity anomalies (smoothed by a three-month running mean) for the central Rockall Channel, January 1972-December 1982.

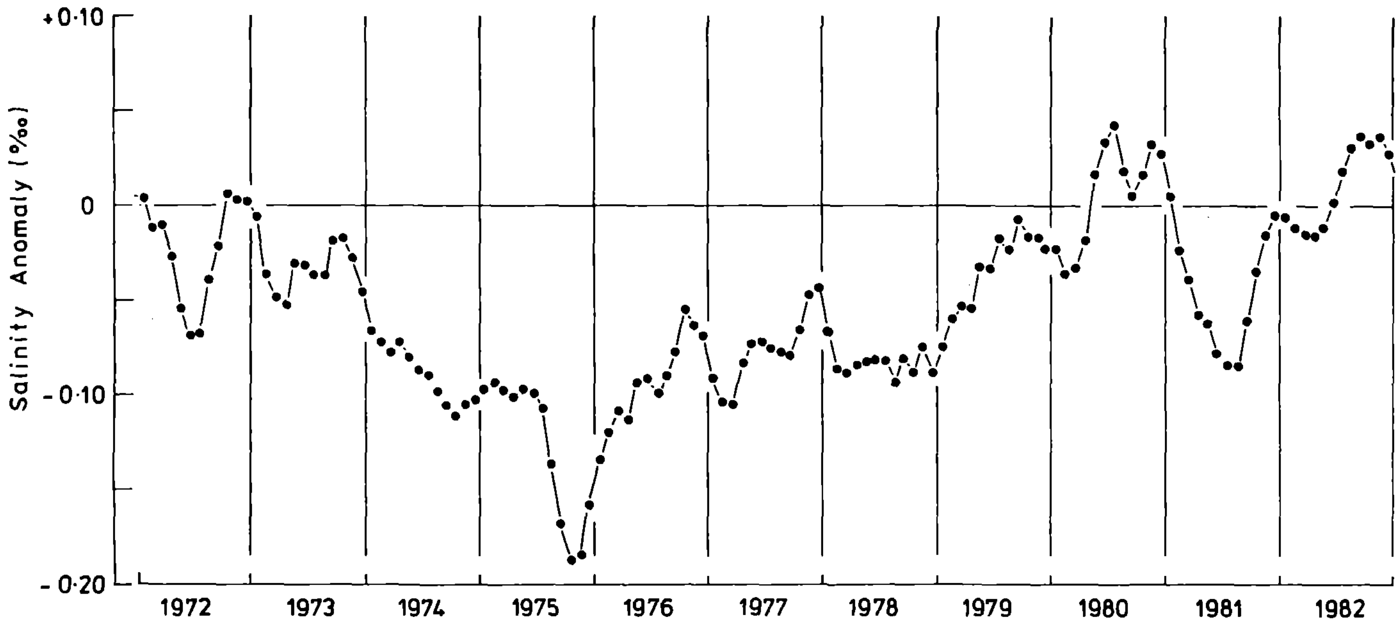

Figure 4.5 Hodographs of monthly residual currents from upper current meters at moorings F (April 1981-October 1982) and P (April 1982-September 1982).

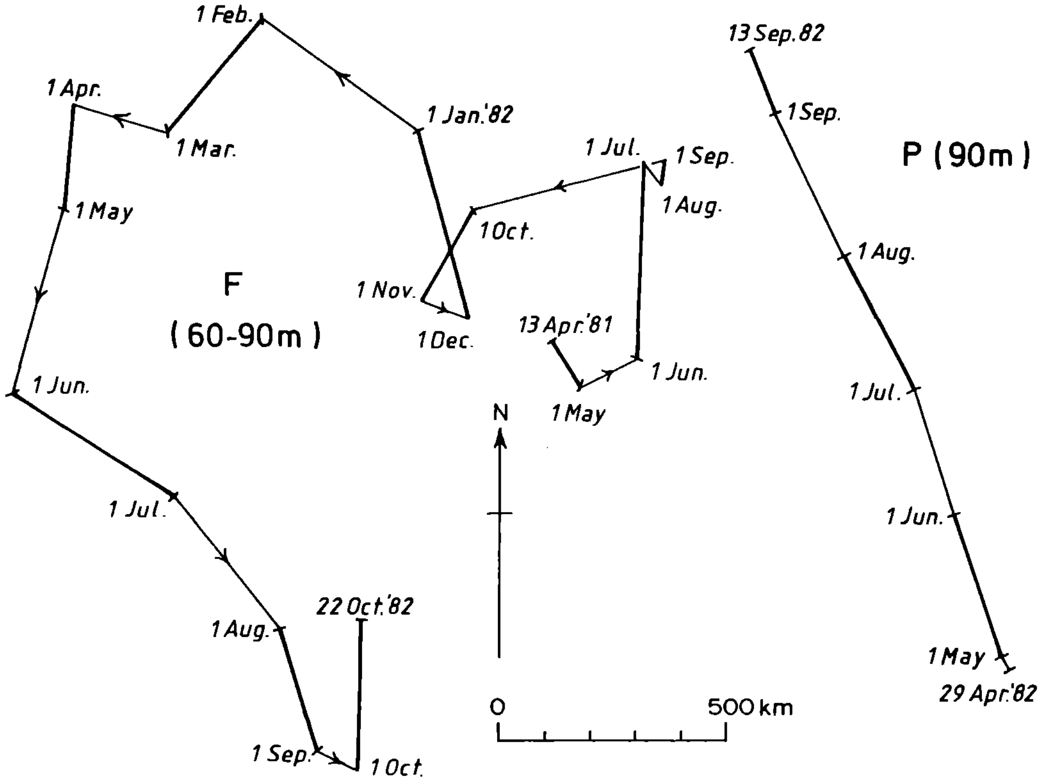

Table 4.1 Overall northerly and southerly components

Year	Mooring F		Mooring M	
	Months with residuel N component	Months with residual S component	Months with residual N component	Months with residual S component
1978	5.5	2	2.5	4
1979	6	1	2.5	3.5
1980	2	—	1.5	4
1981	4	4.5	1.5	4.5
1982	2.5	7	4	5.5

below the 500 m level, with periods of complete residual. At L1 in 500 m depth, operated during October 1981 to May 1982, an upper current meter at residual. At L1 in 500 m depth, operated during October 1981 to May 1982, an upper current meter at 270 m had currents which reversed between north and south, but gave an overall northerly residual of 3 km/day. However, at the 450 m level a much steadier northward current averaging 7 km/day was found. Further data on the slope currents west of Britain has been gathered during Autumn 1982 to Spring 1983 in an intensive cooperative investigation of five UK laboratories, and these records are now in the course of examination.

Currents on the shelf west of Scotland

Recently interest has centred upon the coastal current running northwards from the Irish Sea to the north coast of Scotland. Moorings Y and Z (Fig. 4.1) each gave northerly residuals of about 2.5 km/day during deployments between April and August 1981. Taken in conjunction with temperature and salinity surveys, these results suggest a northward transport for the coastal current of the order of 2×10^4 m^3/s in the summer of 1981, contrasting with a value of 10×10^4 m^3/s obtained from radiocaesium surveys in May 1976. Winter transports may be generally higher. During January-February 1982 the northerly residual at Y averaged 14 km/day over 26 days, but at Z during May to September 1982 the northerly flow was close to the previous summer value, at2.8 km/day.

Postcript

Brief results for the past few years have been given for a number of continuing data series. Some discussion of the causes of the variations observed in the salinity series has appeared elsewhere (*World Climate Programme Report WCP 21*, pp. 245-64), but for the current meter observations more data and further analyses are required before firm suggestions can be made. For present purposes it is probably sufficient for us to indicate the types and locations of data being acquired, and to suggest the sorts of results which can be offered fairly promptly. As this series of publications evolves, a useful consensus should emerge as to the ways in which differing sets of time-series data can be presented in order to be of best use to fellow workers in climatic change.

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5. A time series of model hindcast ocean currents

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Following more than a decade and a half of development, oceanic general circulation models are now beginning to produce qualitatively realistic simulations of dominant ocean features, including the structure and variability of ocean currents on a variety of space and time scales. As demonstrated by Schmitz and Holland (1982), a great deal of quantitative information can be learned about the model, and about the ocean circulation itself, from a detailed comparison of the statistical properties of the modelled and observed flow fields. In this short chapter, the power spectrum of currents from a long-term model hindcast of the large-scale circulation in the central mid-latitude North Pacific Ocean is described and the need for long-term time series of current measurements from various parts of the open ocean is emphasized.

The hindcast was made using a three-dimensional, primitive equation model in a closed rectangular basin having a flat bottom and rigid lid. The model domain extends from the equator to 65°N and from 145°E to 125°W, with horizontal grid spacing of approximately 3° of longitude and 2° of latitude. There are 20 levels in the vertical with grid spacing varying from 10 m near the surface to 100 m at 500 m depth. Salinity is neglected. The model has non-linear horizontal eddy viscosity and conductivity, as well as a small amount of vertical eddy viscosity and conductivity which is appropriate for the deep ocean. Additional vertical mixing of heat and momentum is parameterized by a dynamic adjustment mechanism (Adamec *et al.* 1981) which is based on a critical Richardson number law. The boundary conditions are those appropriate for an enclosed, thermally insulated basin. The surface fluxes that drive the hind-cast are calculated from prescribed fields of solar radiation, clouds, surface air temperature, relative humidity and winds. The winds are taken from six-hourly synoptic analyses made at the Fleet Numerical Oceanography Center (Lazanoff and Stevenson, 1978), while the other fields are taken from zonally averaged monthly climatologies.

It should be noted that the surface heat fluxes computed from this type of boundary condition will always be such as to thermally couple the model sea-surface temperature (SST) to a prescribed "apparent" atmospheric equilibrium temperature (Haney, 1971). As a result, any SST variability that might tend to develop in the model as a result of wind forcing or other internal dynamical process will be thermally damped by the computed surface heat flux. This hindcast experiment is therefore designed to investigatge ocean variability which is essentially *driven* by the wind and *damped* by the surface heating.

The model simulation extended for a total of 30 years. During this period, monthly mean values representing the annual cycle of solar radiation, clouds, surface air temperature and relative humidity were repeated each year, and the observed winds for the 10-year period 1969-78 were repeated three times — once for each decade. Although the same 10 years of observed winds were used for each 10-year period, the ocean model was continually advanced in time (spun-up) over the full 30 years, because each decade after the first one was initialized using ocean model data averaged over the last two weeks of the previous decade. The first two decades are considered to be a spin-up period and the third decade is compared with observations for the ten years 1969-78.

The power spectrum of the model hindcast meridional currents at 42°N, 150°W computed over a particular one-year period near the end of the hindcast is shown in Fig. 5.1. The power spectrum of the hindcast zonal current (not shown) is similar. These spectra show a number of interesting features which we would like to be able to compare with observations. The most prominent peak in the spectrum near 1.0 cycles per day (cpd) is the inertial motion in the model. This peak occurs at a lower frequency than the true inertial frequency at 42°N which is about 1.35 cpd. The shift in the frequency is due in part to the use of a trapezoidal implicit time-differencing scheme and a time step, Δt, of 3 hours in the model. At 42°N, the true phase change in one time step for an inertial oscillation, $f\Delta t$, is approximately 1.0 cpd. In this situation, the implicit time-differencing scheme under-estimates the phase change by about 10 percent, thus lowering the frequency of the computed oscillation. We do not know the effect of this particular feature on any of the other model processes such as vertical mixing and horizontal advection. However, we have been able to determine that the vertical shear of the inertial motion in this model makes an important contribution to lowering the Richardson number to the critical value, and hence to maintaining a relatively high level of vertical turbulent mixing of heat and momentum in the near-surface layers. Since the only mixing mechanism in this model is the dynamic instability mechanism (critical Richardson number law), we don't know how general this result is. Comparisons with observations and other model hindcasts are needed for such an assessment.

Another interesting feature shown in Fig. 5.1 is the change of the power spectrum of the currents with depth. In the top three levels shown, i.e. above 72 m, the peak at the inertial frequency is comparable in magnitude to that at sub-inertial (synoptic and seasonal) frequencies, while at 313 m, the inertial peak is much weaker. This decrease of the inertial motion with depth, which actually occurs more rapidly than is evident from the model levels shown in Fig. 5.1, is consistent with both observations and linear theory (see, for example, Pollard (1980) and Thomson and Huggett (1981) for excellent reviews). As noted previously, the rapid decrease of the inertial motion with depth contributes importantly to the vertical shear of the horizontal currents, and hence to vertical mixing, in this model. Lastly, it can be seen in Fig. 5.1 that the motions at sub-inertial frequencies decrease somewhat between the surface and 72 m, but below 72 m they change very little with depth. In this model, therefore, the low frequency motions at 72 m appear to be more a part of the large-scale circulation in the main thermocline than that of the surface layer.

To validate these modelled ocean currents, long-term time series of current measurements from various parts of the open ocean are needed. We would like to validate the power spectrum of model hindcast currents over as broad a range of frequencies as is possible; including inertial, synoptic, seasonal and interannual time scales. We would also like to compare these with observations of the power spectrum at various depths and at various geographical locations. We are most interested in verifying the generation and the space/time distribution of energetic current systems at synoptic and near-inertial frequencies, because these play a very important role in the parameterized turbulent mixing processes in the model. Upper ocean currents and their frequency distribution are fundamental characteristics of ocean models which should be compared quantitatively with observations. For this to be done properly, long-term time series of upper ocean currents are specifically required.

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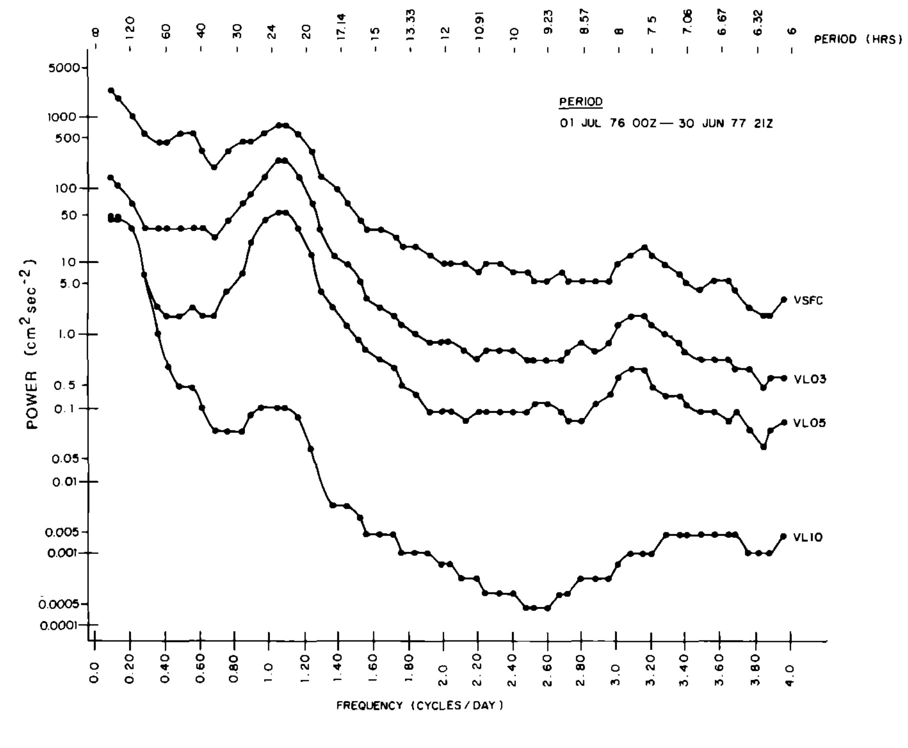
Figure 5.1 Power spectrum of the northward velocity component from model levels 1 (VSFC), 3 (VL03), 5 (VL05), and 10 (VL10) which are located at depths of 5, 31, 72 and 313 m, respectively. Model data were sampled every time step (3h) during the period July 1976-June 1977.



6. Variations in baroclinic structure on a meridional section between New Caledonia and Japan, 1979-82

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Since 1979, all the available expendable bathythermograph (XBT) observations in the tropical Pacific have been collected with the objective of describing large-scale variability of the three-dimensional temperature field, and testing its interpretation as a response to forcing by the trade winds. The real value of the XBT field programme for time series studies will be realized only after several years of observations are available; however the first few years are promising. In this chapter the basin wide geographical coverage obtained is shown, the variability in depth of the thermocline observed in a certain subset of the data is described and the hypothesis tested that it is locally forced by Ekman pumping. Finally, the results are compared to earlier studies of Ekman pumping and generation of planetary waves.

Fig. 6.1 shows the location of XBT drops on bimonthly maps for 1980. A sequence of bimonthly maps like these for the period from 1979 to 1982 are also available. It can be seen that the XBT observations are now spred throughout the tropical Pacific during each bimonth, with a few obvious gaps. Fig. 6.2 contains all the observations for 1979 and 1980 on one map and clearly shows where observations are or are not available. Coverage in the south Pacific has increased significantly over what it was previously. Most of the transequatorial sections are made by merchant ships-of-opportuniuty. These move about in a quasi-random fashion, especially in the "swath" through the central Pacific where they call at a variety of ports at either end of the section. A few merchant ships tend to sail repeatedly over the same route (heavy black lines in Fig. 6.2).

There are two ways to analyze this type of data set. One is to construct horizontal maps of the temperature field using oiptimum interpolation to grid the random arrays of data. The second is to analyze the vertical sections which are repeated over nearly the same route in time-series fashion. An analysis of the repeated New Caledonia-Japan section is presented in this paper. The section crosses the equator near 160°E. Normally one or two sections are obtained each month, except for periods when there are serious human or mechanical failures, or when the ship has been routed off the track.

Fig. 6.3 shows a typical vertical temperature section from 20°S to 30°N, and 0-400 m on the route. Sections like that in Fig. 6.3 are plotted by computer for all the transequatorial cruises as part of the normal data editing and quality control procedures. This section shows the main features of baroclinic structure in the western tropical Pacific.

(1) The thick layer of warm water near the surface bounded by fronts near 20°N and 20°S.
(2) A ridge in the thermocline near 8°N indicating shear in the North Equatorial Current and Countercurrent.
(3) Spreading of the thermocline at the equator, with shallow isotherms upwelling, deep isotherms downwelling.
(4) Centers of the subtropical gyres, displace poleward with depth.

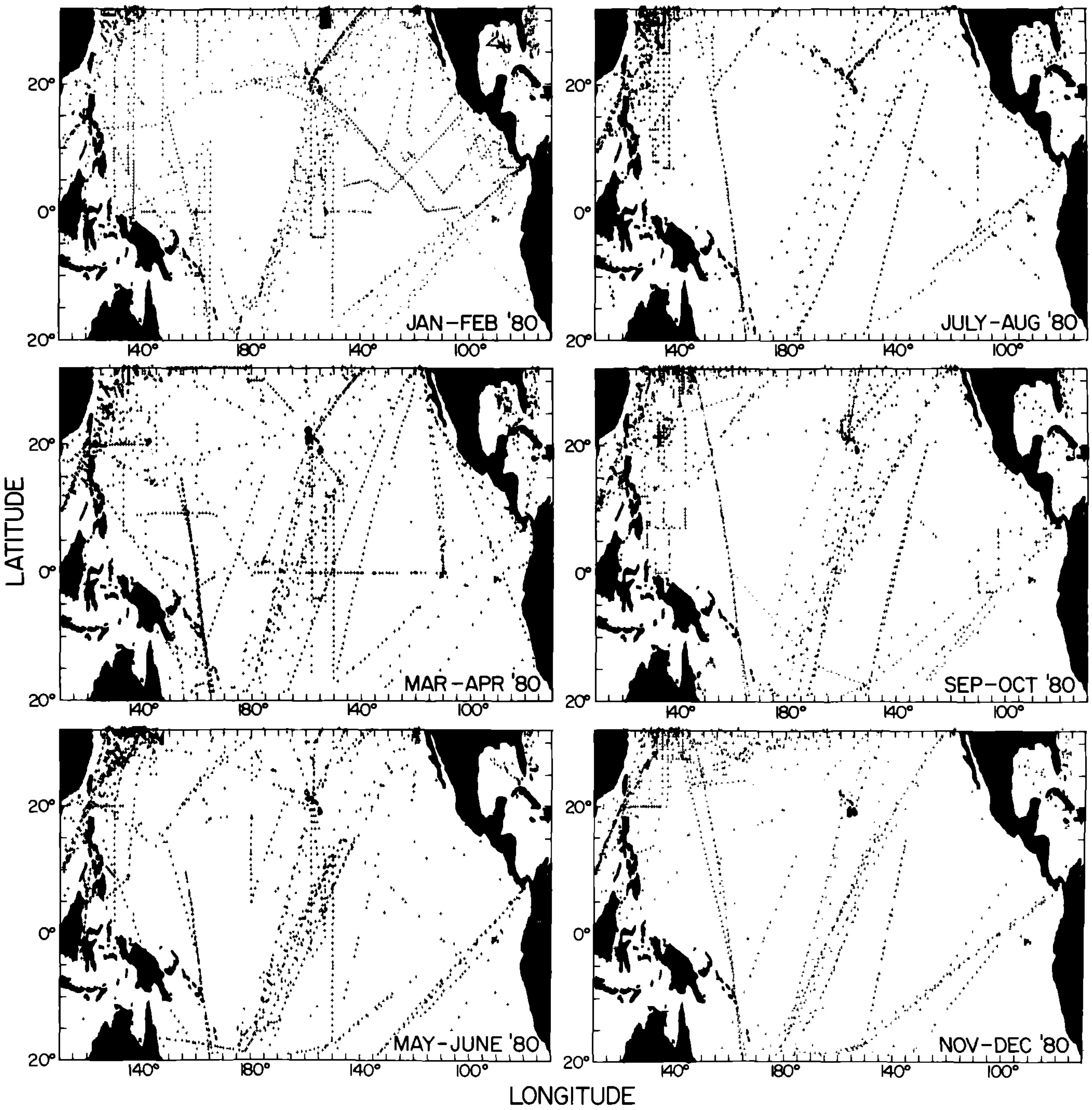
Each of these features is expected to have an observable variability over long time periods. The emphasis of this chapter is on the variability of the ridge/trough system in the thermocline between the equator and 15°N: the baroclinic structure associated with the strength of the North Equatorial Current and Countercurrent. The depth of 20°N isotherm shows the ridge/trough structure at the level of maximum vertical temperature gradient. It also shows fronts at 20° and 28°N, the center of the subtropical gyre near 20°N, and a generally flat topography crossing the equator and in the southern hemisphere.

Fig. 6.4 shows a north-south section of variability in the depth of 20°C from 20°S to 22°N, from June 1979 to May 1982. The greatest variability is at the ridge and trough between the equator and 15°N. During the first two years the ridge and trough oscillated out of phase, with enhanced topography during December-January, and relatively flat topography during May-June. This seasonal signal didn't develop during the 1981-82 period, although the failings are not clear owing to a gap in the observations.

Other features of interest in this section are a ridge/trough system in the southern hemisphere near 10°S. This system is smaller in structure than in the northern hemisphere and it is not as distinctly variable. The front near 20°N is a persistent feature, always appearing when data density is sufficient to resolve it. No seasonal variability in the front is apparent at the depth of the 20°C isotherm, but there is higher frequency variability.

Fig. 6.5 shows depth of 20°C at the northern hemisphere ridge and trough. It emphasizes the locations where variation was largest in Fig. 6.4. Several observations have been averaged in space and time to produce the monthly values. The first two years show the seasonal oscillations, out of phase at ridge and trough, as already mentioned. The difference between the two curves is an index of strength of the North Equatorial Countercurrent. For example, the current was strong during

Figure 6.1 XBT distribution FGGE 1980.



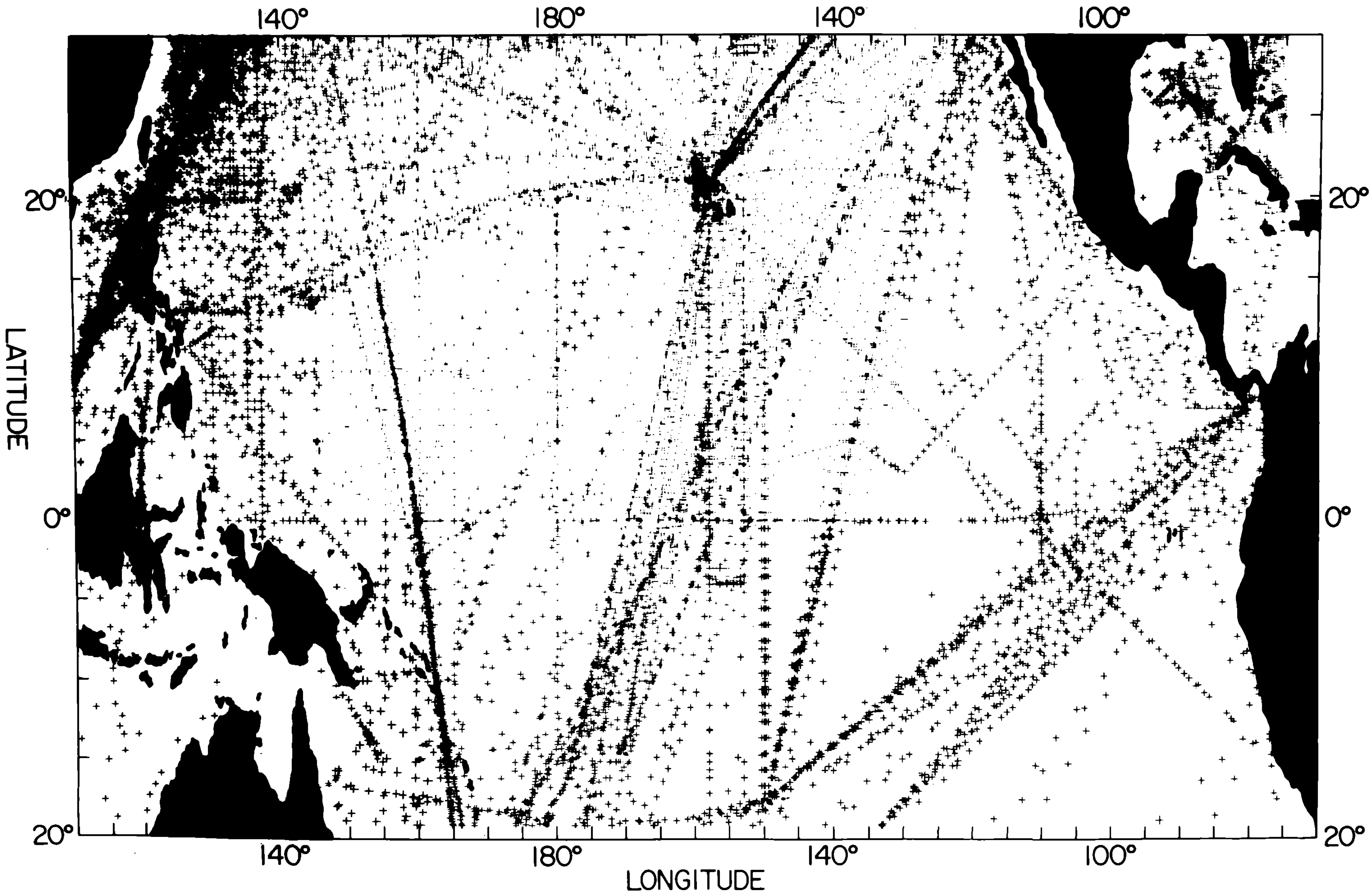


Figure 6.2 XBT distribution FGGE 1979-80.

Figure 6.3 Temperature versus depth, 15 May 1982 - 25 May 1982 — 147°E, 29°N to 166°E, 20°S.

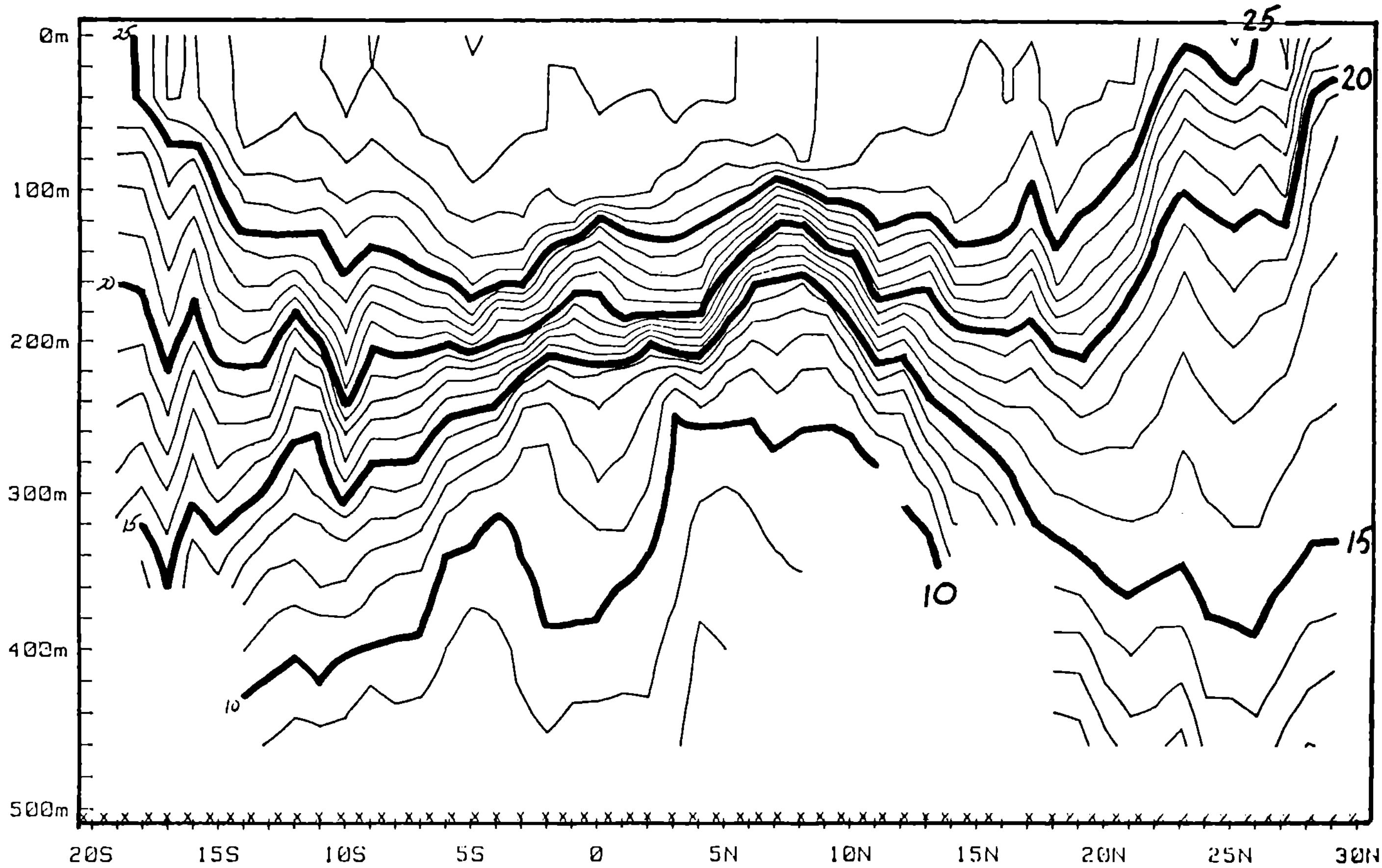


Figure 6.4 Depth of 20°C — New Caledonia-Japan.

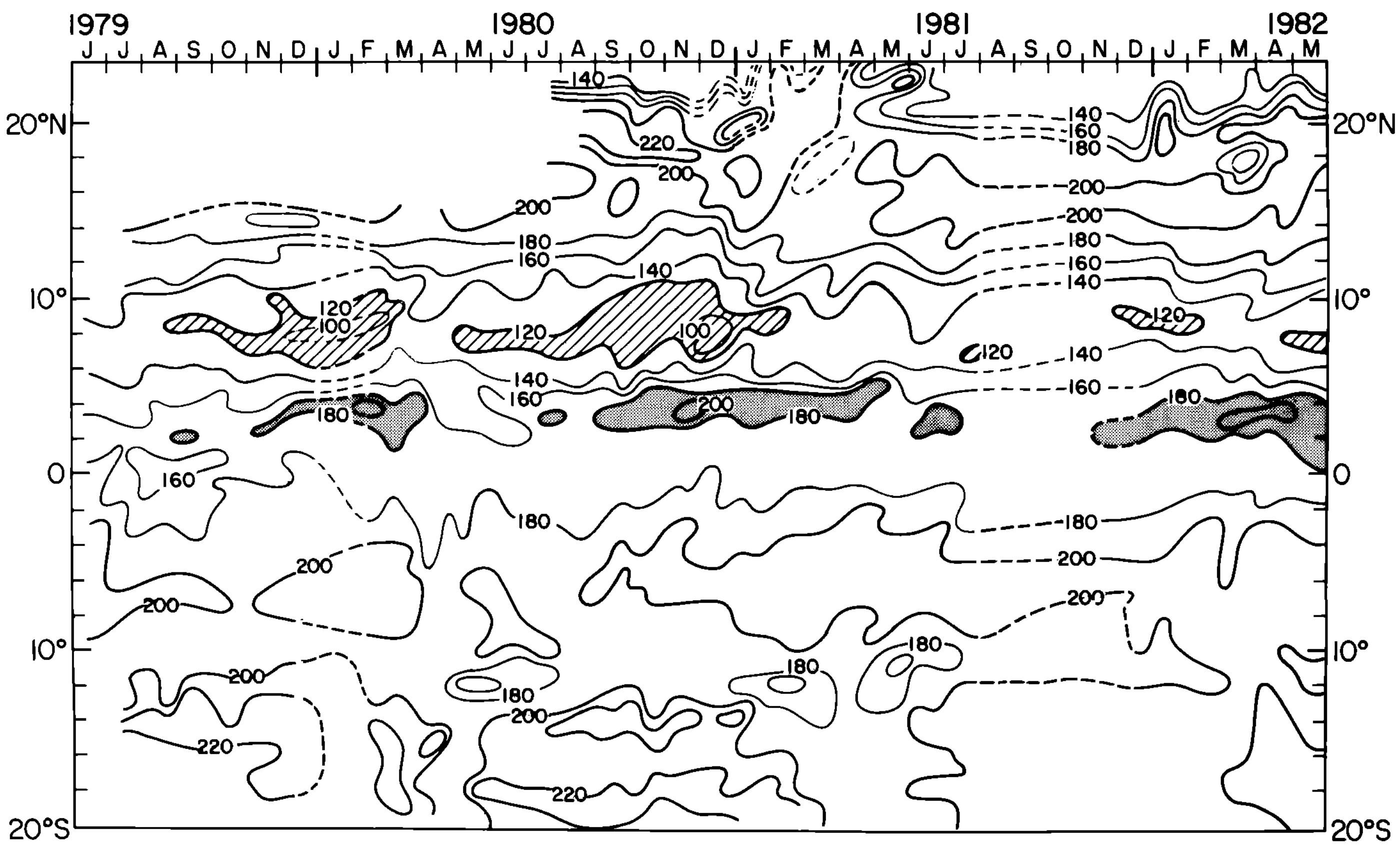


Figure 6.5 Depth of 20°C 160°E.

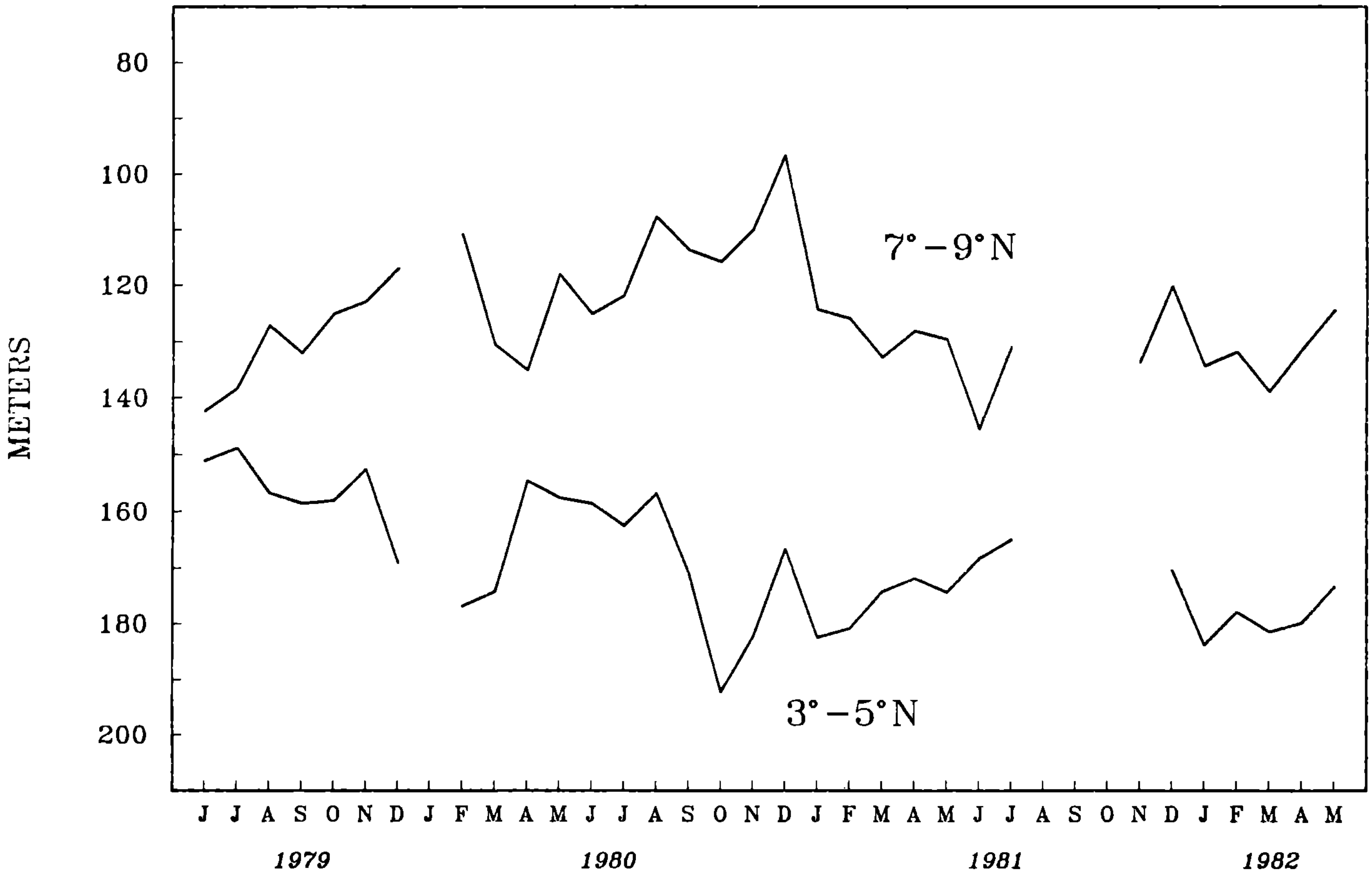
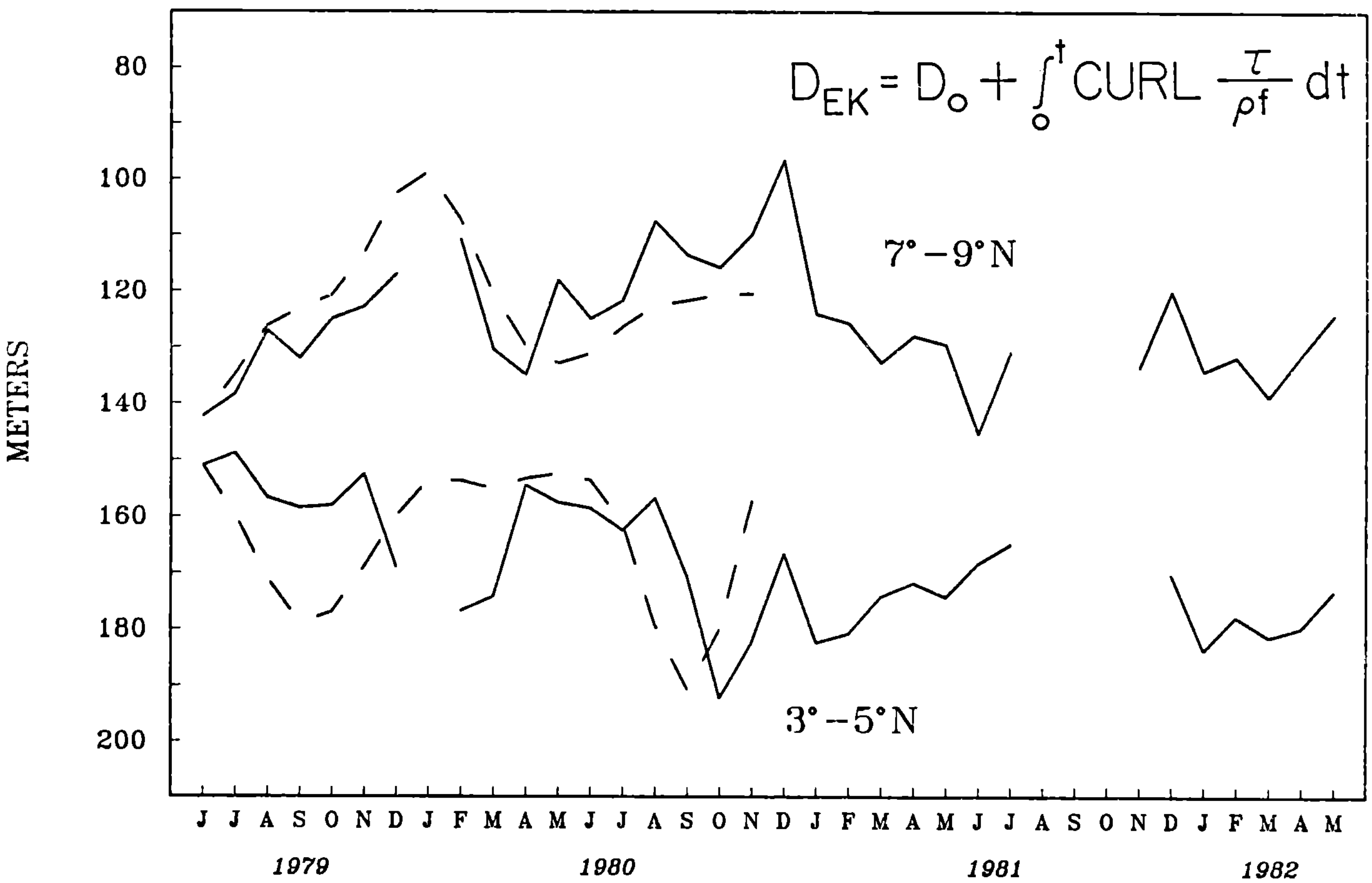


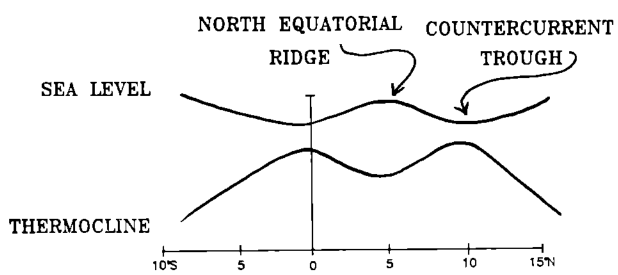
Figure 6.6 Depth of 20°C Ekman pumping 160°E.



December-January of 1979-80 and 1980-81. This strong seasonal signal did not develop in 1981-82, when the variability at both ridge and trough were in phase during a six-month period. Observations since 1979, therefore, indicate a change in seasonality of the baroclinic structure.

The change in seasonality has been observed several times in historical sea level records over the past 30 years. In a recently published article (Meyers, 1982) sea level records have been interpreted for an indication of bimodal seasonal cycles and now similar interpretations are being made from XBTs. The seasonal cycle is forced by the wind. Peaks develop during the latter part of the year, as in 1979 and 1980, when westerly winds blow over the western Pacific throughout the year. The area covered by westerly winds is seasonally modulated, which forces the year-long signal. Extreme examples of this condition are El Nino-Southern Oscillation episodes. Semi-annual oscillations such as the one in early 1982 occur when the easterly trade winds are strong throughout the year, and blow all the way across the equatorial Pacific, at least during winter of the southern hemisphere. The equatorial trades strengthen twice each year, once for winter of each hemisphere, which forces the semi annual signals.

Figure 6.7 Summary of earlier studies of baroclinic structure near the North Equatorial Countercurrent.



Previous studies	Type of data	Location
(1) Meyers (1975)	Individual cruises	150°W
(2) DeWitt and Leetma (1978)	Individual cruises	120°W
(3) Meyers (1979)	Climatology	90°W-150°E
(4) Donguy *et al.* (1982)	Individual cruises	160°E-180°

Was local Ekman pumping in phase with observed depth of thermocline ?

	Western	Central	Eastern
Countercurrent Trough	yes	yes	yes
North Eq. Ridge	not always	not always	yes

An attempt to relate observed variation in depth of 20°C to wind forcing by the simplest possible model — local Ekman pumping — is shown in Fig. 6.6. As is often the case with oceanographic experiments, the analysis of the wind field is incomplete. Fig. 6.6 is therefore presented as a preliminary result. The observed values from Fig. 6.5 are compared to the displacement produced by time-integration of the vertical Ekman pumping velocity. The good correspondence in phase suggests that local Ekman pumping of the thermocline is an important process in the western tropical Pacific, but there are obvious discrepancies.

The results of this tudy are summarized in Fig. 6.7 and compared to earlier studies. The schematic (at the top of Fig. 6.7) shows the sea level and depth of the thermocline on a meridional section through the tropical Pacific. Earlier studies of Ekman pumping and variability of the thermocline depth are identified and the type of data used (synoptic or climatological) and the region studied are given.

Finally, regions where Ekman pumping has been observed to be in phase with the thermocline depth, according to earlier and present studies are indicated.

An important influence of local forçing has been observed at the Countercurrent Trough all across the Pacific. The influence has been observed at the North Equatorial Ridge only in the east. There are always discrepancies between the observed thermocline and the displacements calculated from pumping. Dynamics suggest that they could be due to propagation of long planetary waves generated by pumping. The discrepancy at the North Equatorial Ridge in the central Pacific may be due to waves propagaging away from a region of very intense forcing farther east. This study has been concerned with the local forcing and response at isolated points. It remains to study wave propagation by taking advantage of the spatial coverage provided by the present XBT network as shown in Fig. 6.1. If the very long waves are present, they will be in this data set.

In conclusion, it should be emphasized that both local Ekman pumping and the generation of planetary waves are very sensitive to the detailed space/time structure of the wind field. For any further analysis, therefore, of this data set, the most realistic wind field should be used.

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7. Variation of the sea surface temperature across the Kuroshio in the Tokara Strait

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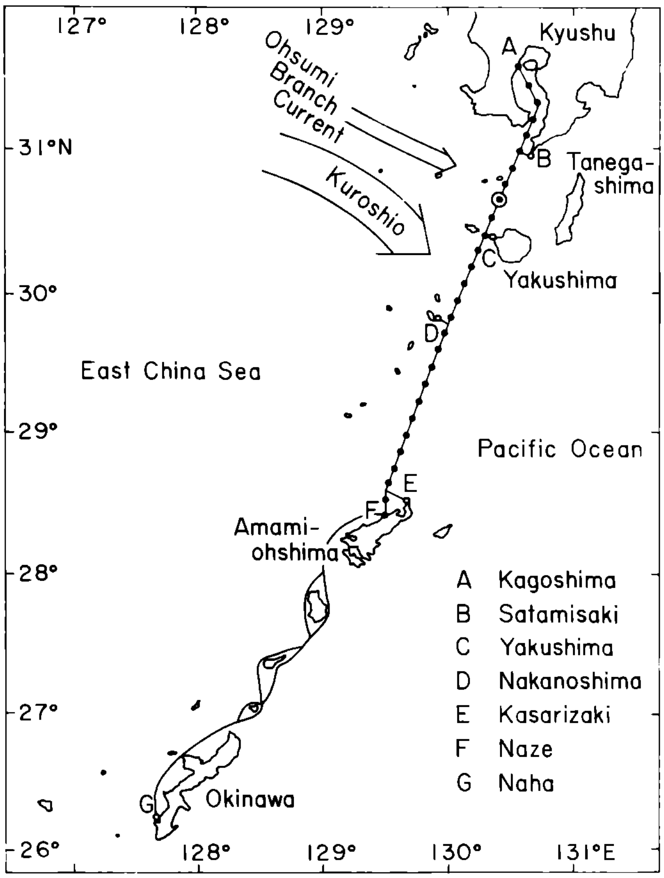
The Kuroshio enters the East China Sea off the coast of Taiwan and flows northeastward along the continental shelf. It leaves the shelf edge at about 29°N, and turns southeastward at about 30°N, 128°E to flow out into the Pacific Ocean through the northern part of the Tokara Strait (Fig. 7.1). The Tokara Strait for the Kuroshio may be regarded as a counterpart of the Florida Strait for the Gulf Stream system.

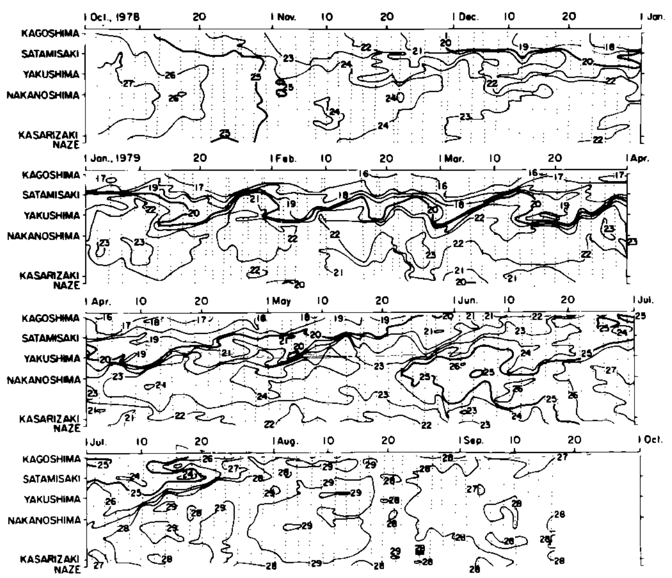
Figure 7.1 Ship course and stations at which sea surface temperature was analyzed (•). The temperature variation at the station indicated by (•) is shown in Fig. 7.3.



As one of the projects belonging to the Kuroshio Exploitation Research sponsored by the Science and Technology Agency of Japan, the Kagoshima Prefectural Experimental Fishery Station installed a self-recording thermometer in the cooling-water intake pipe of the passenger-boat *Emerald-Amami* which is a regular liner between Kagoshima and Naha, and has observed the sea surface temperature across the Kuroshio in the Tokara Strait since October 1978. The effective depth of the measurement is 5.8 m below the sea surface, and the typical interval of the observation is two days. The measurement program is continuing and similar measurements are being made between Tokyo and Hachijo Island by the Tokyo Metropolitan Experimentary Fishery Station.

The time-space diagram of the sea surface temperature across the Tokara Strait is shown in Fig. 7.2 from October 1978 to September 1979. The continuous measurement of the sea surface temperature profile across the strait seems to be a good tool for monitoring the position of the Kuroshio (or the Kuroshio front) at least from late autumn to early summer when the horizontal temperature gradient is significant in the surface layer. The position of the temperature front varies considerably between Satamisaki and Nakanoshima. When the strong gradient appears near Satamisaki, a considerable amount of the Kuroshio water passes through the Ohsumi Strait between Kyushu and Tanegashima. Such a current is called the Ohsumi Branch Current. The horizontal temperature contrast is relatively large from the middle of October to late July, and very small from early August to the middle of October. The phase of the seasonal variation of the temperature contrast is

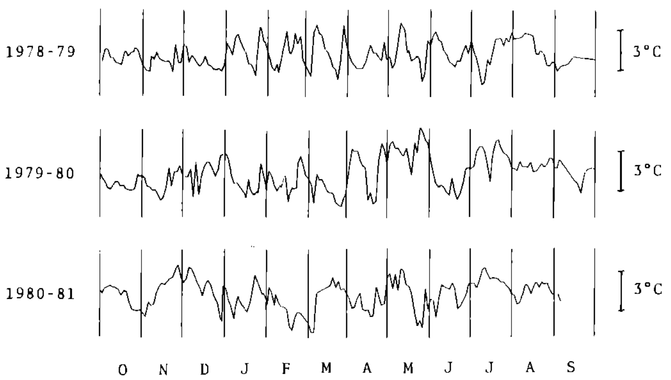
Figure 7.2 Space-time diagram of the sea surface temperature in °C from Kagoshima to Naze from October 1978 to September 1979.



shifted by a few months from that of the temperature itself. The transition is somewhat abrupt, though the transition time is changeable year by year.

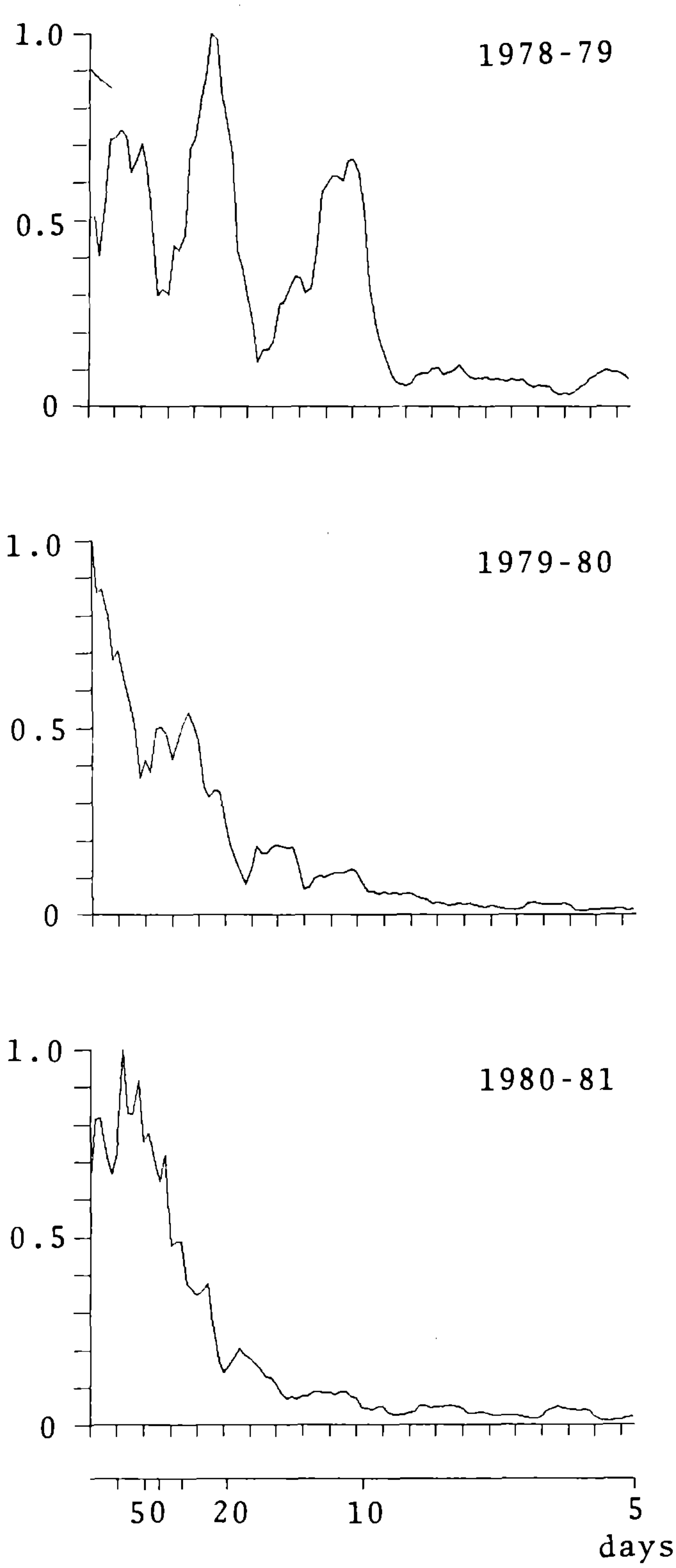
In addition to the seasonal variations, the water temperature at a fixed position exhibits complicated variations with a period of several tens of days. An example of the short period variation (annual and semiannual components have been eliminated) is shown in Fig. 7.3 for the point between Satamisaki and Yakushima (see Fig. 7.1 for the position) which is located usually inside of the temperature front of the Kuroshio. The power spectra of the temperature variation were calculated for each segment of one year length starting from the first of October and are shown in Fig. 7.4. In the first year starting from October 1978, a very periodical variation with a period of about 20 days was observed. This component of the variation was predominant for all points inside of the frontal zone which is located between Satamisaki and Nakanoshima.

Figure 7.3 Example of the short period variations of the sea surface temperature at a fixed position. Annual and semi-annual components have been removed.



However, the situation changed from year to year. The dominant spectral peak is seen at about 25 days in the second year and at about 50 days in the third year. The nature of short period variation and its interannual change are now under examination in connection with the possible forces and other relating phenomena such as regional wind variations and sea level variations.

Figure 7.4 Power spectra of the temperature variation. Spectral values are normalized by the maximum value of each spectrum. →



8. Examination of time series data at OWS TANGO

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Department of Geophysics, Tohoku University, Japan

Ocean Weather Station T (TANGO) is located in the area adjacent to the Kuroshio south of Japan (29°N, 135°E). It was operated by the Japan Meteorological Agency from 1948 to 1981, but was replaced recently by an ocean data buoy. During the period of its operation intensive continuous observations were carried out from June 1950 to November 1953. The data is rather old, but it includes marine meteorological elements every three hours and hydrographic serial observations down to 1000 m every other day on average (JMA, 1952-5). The data for the intensive observation period were carefully analysed and evaluated for air-sea fluxes of momentum and heat by use of bulk formulas, as well as for the variation of heat content in the upper 200 m of the water column.

In this chapter, two major findings are briefly reported: (1) we found that convergence of heat by horizontal processes in the sea was significant in the heat budget of the upper ocean of this sea area (Kurasawa *et al.*, 1983), and (2) we obtained appropriate factors of modification for coefficients of bulk formulas when formulas for values of marine meteorological elements averaged for certain periods were used, e.g. ten days, a month, etc. (Hanawa *et al.*, 1983).

The net heat flux through the sea surface and the local time change of heat content of the upper 200 m water column were evaluated for various time scales. Heat convergence in the sea was estimlated as the residual of these.

The striking feature is that the water temperature at various depths varies in a very coherent way, by an order of 1°C in the time scale of two or three days. This does not balance with the surface heat flux and it can be inferred that the temperature variation in this region is mainly caused by advection of small water masses of different temperatures representing the process of horizontal mixing in the sea. Fig. 8.1 shows the monthly heat convergence in the sea. From March to May (shaded in the figure), the heat convergence has a tendency to be large corresponding to the increase of the Kuroshio transport.

By use of the above-mentioned intensive observation data, we examined factors of modification for coefficients of bulk formulas when we used the formulas for values of marine meteorological elements which are averaged for certain periods. One of the important results is shown in Fig. 8.2. Without these modifications, the evaluated wind stresses become smaller when the data averaged for longer periods are used, but for the latent heat flux the differences are smaller with an opposite sign, and for sensible heat flux the difference is insignificant. For the averaging time of a month, the modification factors are 1.45, 0.95 and 1.00, respectively.

The use of vector-averaged wind speed was also examined and a new parameter, 'stability of wind field', was introduced. This was defined by the ratio of vector-averaged wind speed to the scalar-averaged wind speed and its importance and usefulness were discussed. For more detail, see the references.

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Figure 8.1 Monthly mean heat convergence in the sea at OWS TANGO from 1950 to 1953 and its average.

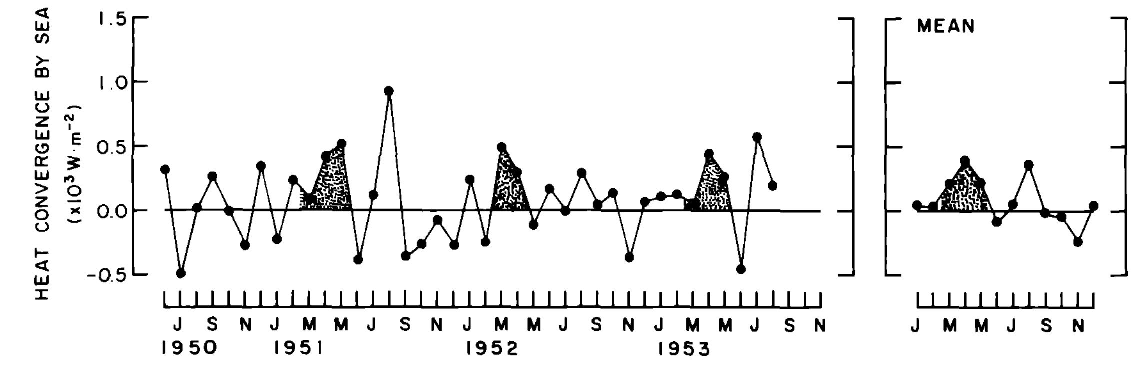
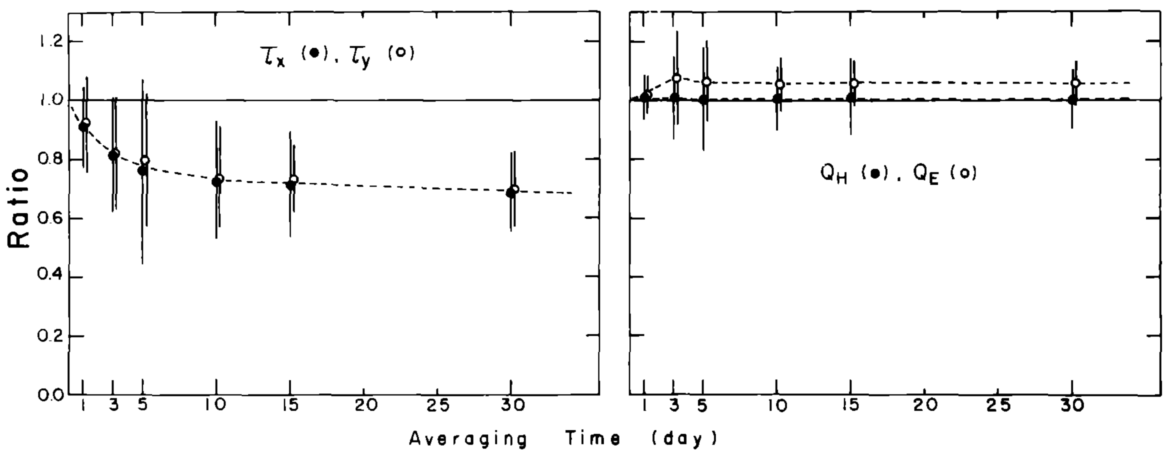


Figure 8.2 Ratio between flux estimates by use of every three-jour data (sampling method) and those by use of averaged data (scalar-averaging method) as a function of the averaging time.

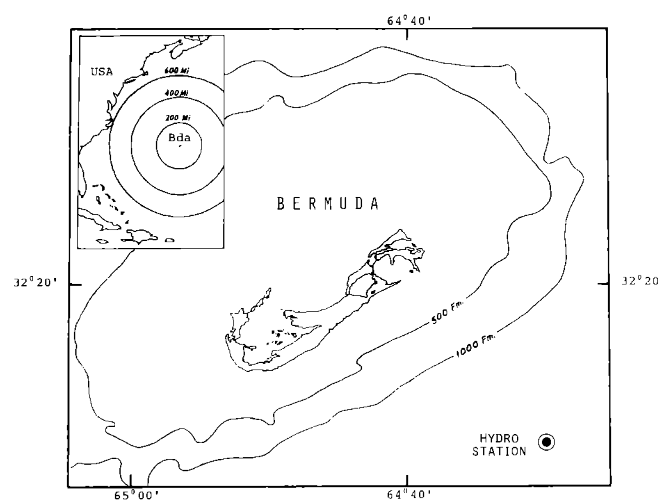


9. Hydrostation 'S' off Bermuda in 1982

W.R. Wright and A.H. Knap
Bermuda Biological Station for Research Inc., Bermuda

The longest series of deep-sea oceanographic stations in the world has been maintained since 1954 at 32°10' N, 64°30' W, 13 miles (20 km) southeast of Bermuda (Fig. 9.1). Since the demise of the weather ships it has been the only regularly reporting station in the western North Atlantic Ocean.

Figure 9.1 Location of Station 'S'.



For 27 years the work was done under a joint arrangement between the Bermuda Biological Station for Research Inc. (BBS) and the Woods Hole Oceanographic Institution (WHOI) with funding from the Office of Naval Research, the Atomic Energy Commission, and, from 1975, the National Science Foundation (NSF). In 1981 NSF began funding the project directly through BBS, with the authors as principal investigators.

The series has been known both as the Panulirus Stations (after the BBS research vessels *Panulirus* and *Panulirus II*, from which all the stations were made through 1982) and as Station 'S' (origin unclear — perhaps for Sargasso Sea, or perhaps Henry Stommel, who instituted the series).

More than 500 stations have been made in 28 years, roughly one every three weeks, although there has been some bias toward the calmer summer months. Each station consists of two Nansen bottle casts with reversing thermometers obtaining temperatures and water samples at 26 depths down to about 2600 m in water depth of 3000 m. Depth is determined with unprotected thermometers. Oxygen and salinity analyses have been run routinely; measurements of nutrients, chlorophyll, primary production and other variables have also been made from time to time. Data reports are available from BBS and the entrire series is on file with the US National Oceanographic Data Center. More than 40 scientific papers have been published using the station data base; a bibliography has been prepared (Wright and Knap, 1981) and can be obtained form BBS.

This report covers stations 488 to 506, from 18 December 1981 through 2 December 1982. These were the last stations to be carried out from *Panulirus II*, which was replaced in January 1983 by R/V *Weatherbird*. The series will continue with the first Station using the R/V *Weatherbird* made on 27 January 1983 (Station 507). From now on the time series will be known only as Station 'S'.

In 1982 there was at least one station every month, with two each month from March through June and three in Septembrer. Oxygen titrations were done at BBS using the modified Winkler method and salinity analyses were done using the BBS Guildline salinometer. Samples for particulate matter analysis were collected monthly to 150 m; samples for trace metals, nutrients and primary production were collected to 150 m every other station; samples were taken each quarter from all depths for helium and tritium analysis by W. Jenkins at WHOI; large volume water samples were analysed occasionaly for trace organics by A.H. Knap; one full cast for beryllium measurement was made on Station 504, to be worked up by C.I. Measures, M.I.T.; and Sargassum (SSP) was collected routinely for analyses of carbonate production by epiphytes by H. Pestana, Colby College. A list of 1982 publications using Hydrostation 'S' data is presented in Table 9.1.

Table 9.1
Papers published in 1982 using hydrostation 'S' data

Jenkins, J. 1982. On the climate of a subtropical ocean gyre: decade timescale variations in water mass renewal in the Sargasso Sea. *J. Mar. Res.*, supplement to vol. 40, pp. 265-90.
McCartney, S. 1982. The subtropical circulation of MODE waters. *J. Mar. Res.*, supplement to vol. 40, pp. 427-64.
Sturges, W. and Summy, A. 1982. Low-frequency temperature fluctuations between Ocean Station Echo and Bermuda. *J. Mar. Res.*, supplement to vol. 40, pp. 727-46.
Talley, L.D. and Raymer, M.E. 1982. Eighteen degree water variability. *J. Mar. Res.*, supplement to vol. 40, pp. 757-75.

The 1982 temperature results, plotted against time in Fig. 9.2 are very similar to the 1954-72 monthly averages prepared by E. Schroeder at WHOI (Fig. 9.3). There is no clear seasonal signal below about 200 m in either case, and the mean isotherm depths in 1982 are within a few meters of the long term averaged annual means (Table 9.2).

Table 9.2
Mean isotherm depths

isotherm	1982	18-year mean
18°C	295 m	283 m
15°C	609 m	601 m
10°C	833 m	826 m
5°C	1253 m	1260 m

The surface summer heating in 1982 was greater than normal, as the 20°C isotherm was about 50 m deeper than the long-term mean. The maximum midsummer surface temperatures were the same, about 27.3°C in August, and the 20°C isotherm appeared in April as usual. However, the water was warmer than 20°C to a depth of 90 m in December 1982 although in the long-term average the December surface temperature is less than 20°C.

Similarly, the 1982 salinity cycle (Fig. 9.4) was very like the long-term picture of Schroeder's (Fig. 9.5) except in the surface layers, where 1982 was both fresher at the surface in summer and fall and more saline (greater than 36.6 ‰) at the salinity maximum at 100 m during the same period. The deeper isolines are all less smooth than in the 18-year picture, as expected, but the deep plunge in the 35 ‰ isohaline in the Fall appears too great to attribute solely to lack of measurement precision in the slack vertical gradient (less than 0.002 ‰ in 10 m) at those depths. It could represent advection through the area of a slightly more saline water mass; however, we feel this may be an anomaly due to leaks in the Nansen bottles used during these casts.

Starting in 1983 the Station 'S' series will be extended to include one station to 4000 m every three months. The observations will be made at 32°07' N, 64°20' W, in 4200 m depth. The purpose of the additional stations is to extend the time series into deeper water and also to provide some idea of how representative Station 'S' may be of locations further offshore.

R/V *WEATHERBIRD* was equipped with these deeper observations in mind. She is a 65-foot steel vessel, built in Louisiana in 1970 and used for research in New England waters under the name *WHITEFOOT* before being purchased by BBS. She is powered by two GM 871 diesel engines and has a cruising speed of 8 knots and a range of 1500 miles. There are two diesel generators (20 kW). Navigational equipment includes two Northstar Loran C receivers and a Racal-Decca satellite navigator. The vessel has 400 square feet of open deck space aft with fittings for installing 12-by-8-foot laboratory vans. One van has been fitted out for hydrographic casts. The hydro-winch is hydraulic with a drum capacity of 6000 m of 3/16" wire. The wire leads directly to a block on a hydraulic J-frame on the starboard side where a small hydro platform has been let into the bulwarks. Because of the increasing demand for additional water samples it is planned to switch to 2.5 and 5-litre Niskin bottles for the standard cast. Reversing thermometers will be used on all bottles, as before.

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Acknowledgement

This work was supported by Grant no. OCE-8116410 from the National Science Foundation.

Figure 9.2 Temperature (°C) from Station 488 to 506 (December 1981 to December 1982) plotted against time. Note depth scale change at 200 m.

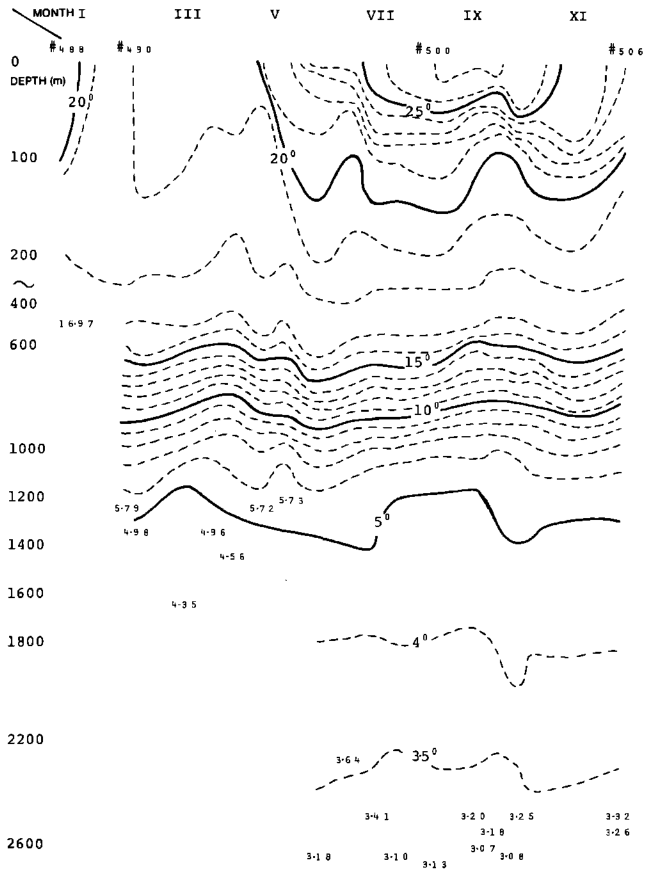


Figure 9.3 Eighteen-year (1954-72) monthly temperature (°C) averages plotted against time. From E. Schroeder's files at WHOI.

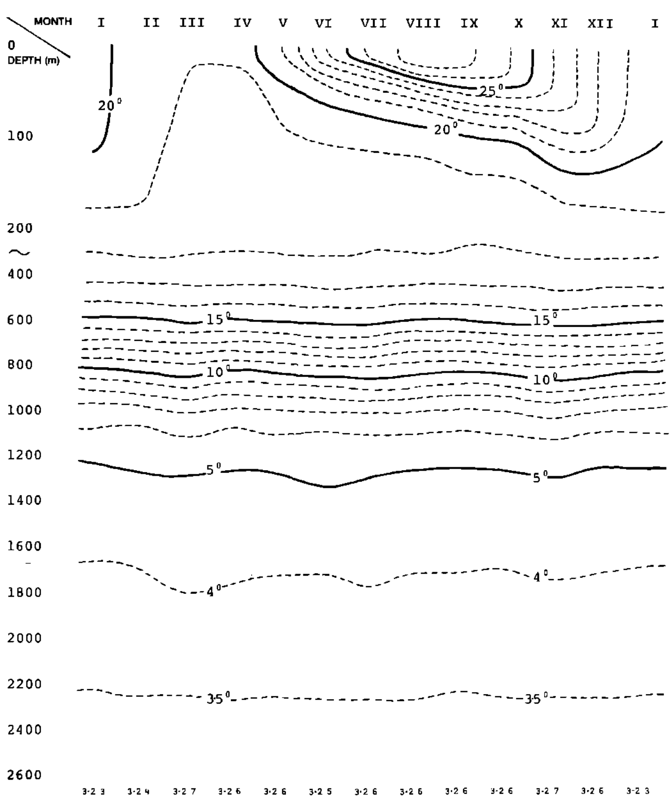


Figure 9.4 Salinity (‰) from Stations 488 to 506 (December 1981 to December 1982) plotted against time.

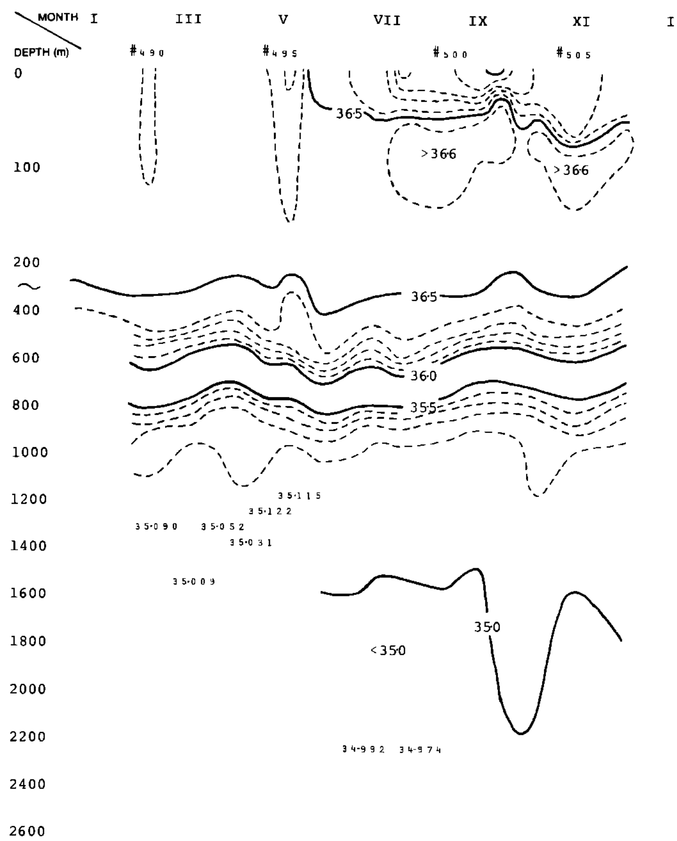
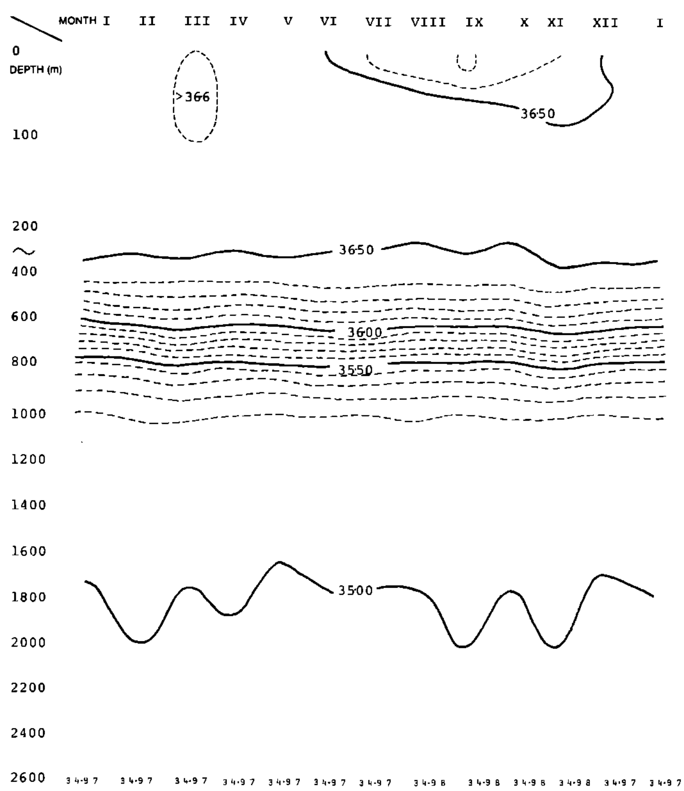


Figure 9.5 Eighteen-year (1954-72) monthly salinity (‰) averages plotted against time. From E. Schroeder's files at WHOI.



10. Oceanographic time series in the Adriatic Sea

Mira Zore-Armanda

Institute of Oceanography and Fisheries, Split, Yugoslavia

Since 1948 the Institute of Oceanography and Fisheries in Split has observed a number of parameters at representative stations in the Adriatic at defined time intervals. Early sampling included only hydrographic parameters, but later the scope was steadily widened to include different dynamic, chemical and biological sampling. Earlier investigations in the Adriatic had indicated that it was subject to regular seasonal and annual variability in its hydrographic properties. These fluctuations influence all kinds of movements of sea water which in turn affect its ecological conditions.

There are three types of permanent stations (Fig. 10.1). The first group of stations (three), in the vicinity of the eastern coast, are sampled monthly. One of them (called Stoncica), close to Vis Island, has the best time series (more than 300 visits) for all parameters.

The second group is a profile across the middle Adriatic. This is the Split-Gargano profile which, together with stations of the first group, yield seasonal data. Their profile coincides with the Palagruza Sill, which separates the two Adriatic Pits (basins): South Adriatic Pit and Jabuka Pit. The profile coincides with the point at which waters form the north and the south Adriatic meet; they can easily be recognized by their different characteristics, the main one being the northern Adriatic's lower salinity. The third group of stations cover the deep part of the two Adriatic Pits. They have been much less regularly visited, but for several years seasonal coverage exists.

Continental characteristics of the Adriatic Sea are reflected by very pronounced seasonal variation. The annual range of surface temperature is 18°C in the south to 25°C in the north. Annual salinity ranges are as marked. In the coastal part of the middle Adriatic they reach 7‰, while in the open sea 2‰. In the northern Adriatic the salinity variation is higher under the influence of the Po river. The morphology of the basin and climatic conditions are responsible for such strong seasonal changes. The Adriatic is an elongated basin and its shelf area in the north is rather shallow. Great differences in meteorological conditions between summer and winter are also typical.

The Adriatic is basically a dilution basin, its salinity increasing to the south, but it is also strongly seasonally dependent. In winter its northern part is the source of cold and rather saline water ($\sigma t = 29.6$). The pronounced seasonal and annual variation of its temperature and salinity results in a corresponding seasonal rhythm in the current system. The most important feature of the whole system is the outgoing surface current in the summer and incoming in winter. The former is compensated by advection from the Ionian Sea in the intermediate layer and the latter by the outflow of water in the bottom layer. Such seasonal rhythm governed by a geostrophic current component is shown very well by the annual variation of current directions at the Stoncica station (Fig. 10.2). On the Split-Gargano profile the longitudinal flow predominates in summer and winter due to the great

Figure 10.1 Map of the Adriatic Sea with permanent stations worked by Institute of Oceanography and Fisheries, Split (depth contours in metres).

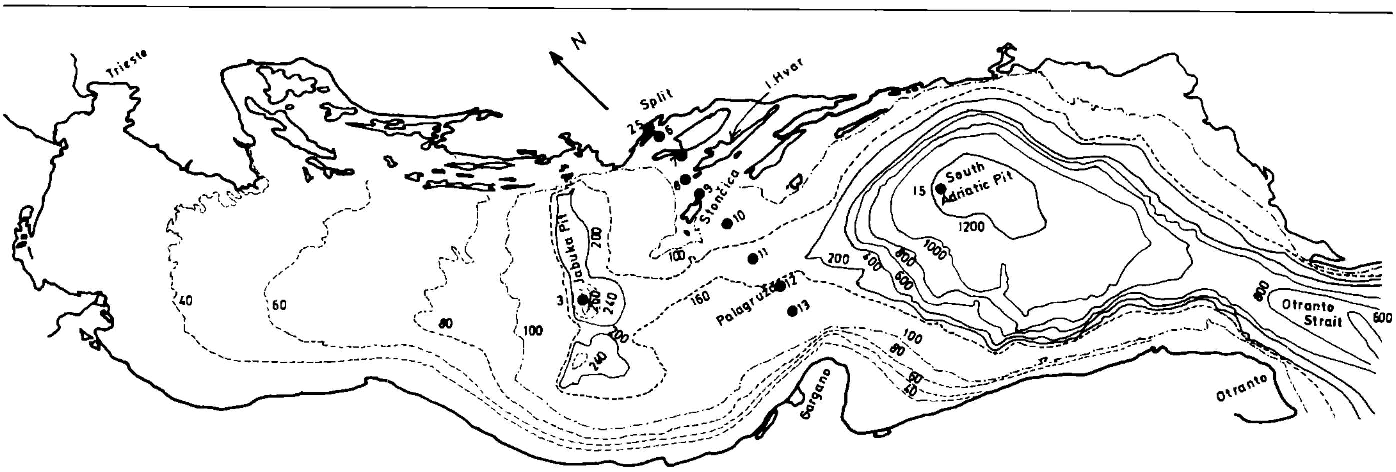


Figure 10.2 The circle shows the sectors of direction of current observed in different seasons in the surface layer at Stoncica permanent station (after Zore-Armanda, 1966).

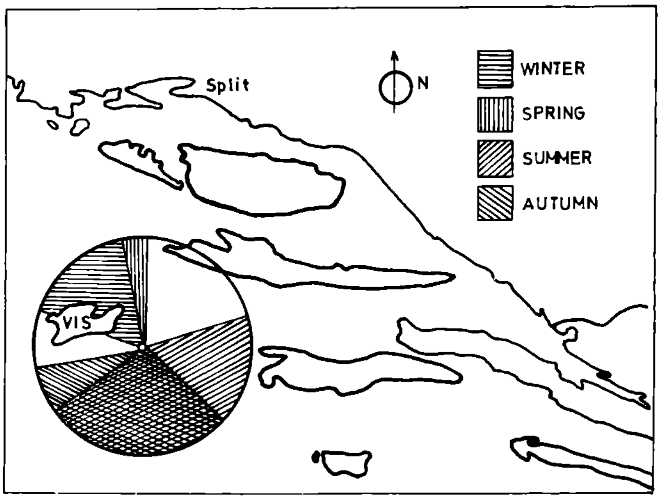
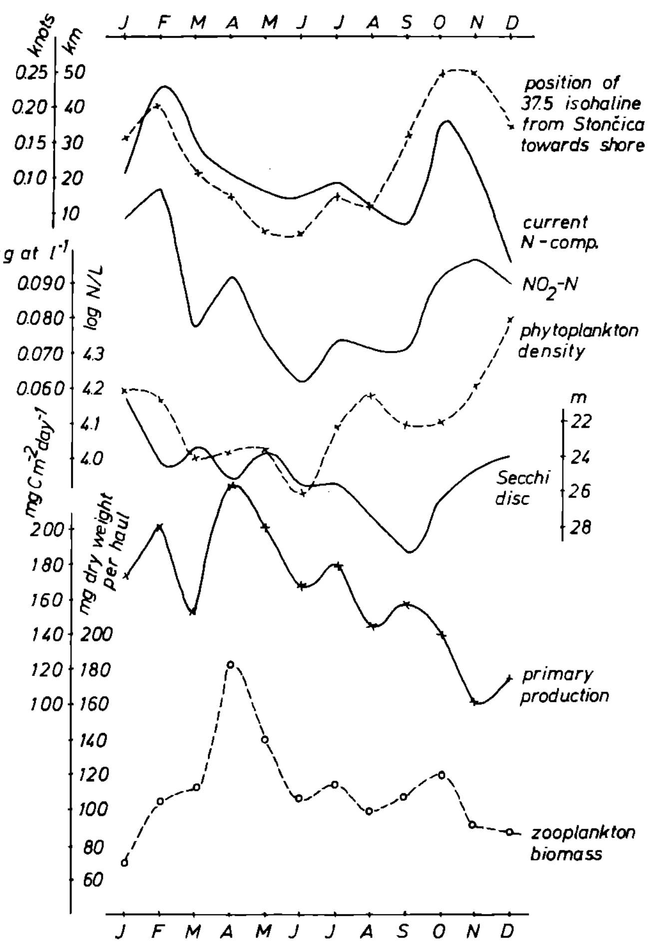


Figure 10.3 Seasonal variation of some parameters at Stoncica permanent station. All data refer to long-term averages. Position of 37.5 isohaline in relation to the coastline and current refer to the surface layer and all other parameters are averaged for all sample depths (station depth is 100 m). Data after Karlovac *et al.* 1974, Buljan and Zore-Amanda, 1979 and unpublished by T. Pucher-Petkovic (phytoplankton density and primary production) and I. Vukadin (nitrite).



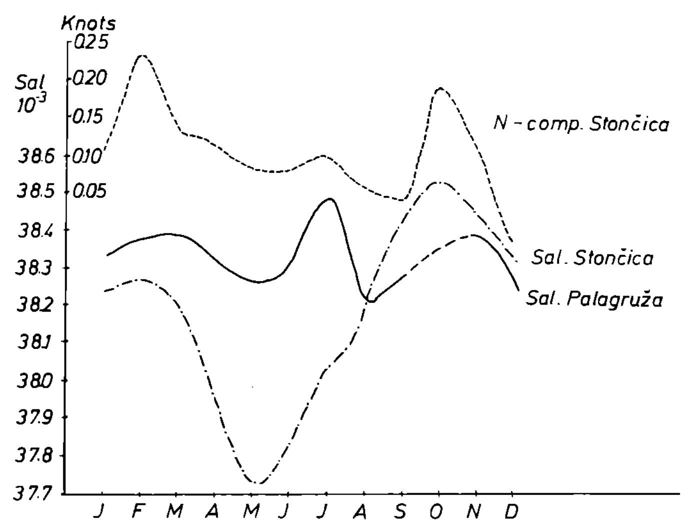
horizontal density gradients between the north and south Adriatic. In spring and autumn however, the transverse flow between the coasts predominates bringing coastal waters to the central parts of the profile. Annual variability of some chemical and biological parameters closely follow such events (Fig. 10.3).

There are also irregularities in the current field at the profile, which can be explained by topographic effects. At the west coast there is a persistent salinity maximum in July (Fig.10.4). It may be the result of advection from the south, but it conflicts with a general trend for surface current outflow in the summer and is understood to be the effect of the sill. This part of the profile is also very productive.

Long-term variations are strongly dependent on the climatic conditions. Salinity variation depends in the first place on the influence of the Mediterranean intermediate water of high salinity. The source of this water is the Levantine basin from which it spreads out at intermediate depths over the whole basin, but not always at the same rate. As this water is the most saline of the Adriatic it can be detected by the core method. It first mixes with Adriatic water in the Otranto Strait, but also at the Palagruza Sill (Split-Gargano profile). Stronger water circulation, or stronger water exchange between the Adriatic and other eastern Mediterranean basins, is manifested by the presence of larger quantities of Levantine water, or by increased salinity in the Adriatic. It is understood that air pressure gradients over the eastern Mediterranean exert an influence on water exchange among its basins. A good correlation exists with air pressure difference between Athens and Trieste and the salinity variation of the Adriatic waters (Fig. 10.5).

The formation of cold or heavy water in the Adriatic also stimulates stronger water exchange, as the heavy winter water of the Adriatic spreads in deep layers over the whole eastern Mediterranean. Winter surface cooling can be connected to the appearance of the cold winds. Typical cold winds are bora (from NE) and the northerly tramontana. The

Figure 10.4 Seasonal variation of sea surface salinity at the west (Palagruza) and east (Stoncica) side of the Split-Gargano transect; the same for the north current component at Stoncica.



pressure pattern which favors cold winds over the Adriatic is correlated to the pressure pattern over the Atlantic, or to the position of the Icelandic Low and Russian High. Further, it has been found that such pressure patterns correlate well with the quantity of ice over the North Atlantic (Fig. 10.6). The long term variation of oceanographic properties and their dependence on climatic conditions can be summarized as follows: the pressure pattern over the Mediterranean and cold air mass intrusions in that area influence the oceanographic characeristics of the Adriatic and are also connected to some oceanographic (ice condition) and meteorological (position of Icelandic Low) conditions of the North Atlantic (see Table 10.1).

The stronger water exchange of the Adriatic and other basins of the eastern Mediterranean favors biological productivity since it increases the level of nutrients in the south and middle Adriatic. It is possible to make a rough calculation of the quantity of nutrients which enter the Adriatic from the nutrient balance in the Otranto Strait. This increase in nutrients is favourable to the primary productivity and biomass of several phytoplankton groups. All such events can also be related to secondary production but with a delay of three years (Fig. 10.7). The total annual catch of fish in the Adriatic has been analysed and accurately predicted by variation in climatic factors.

In conclusion, it can be said that oceanographic time series in the Adriatic Sea have proved to be a valuable tool to study seasonal and long-term variability of different physical, chemical and biological parameters and their interrelatedness.

Figure 10.5 Annual values of salinity for Split-Gargano transect (all sample depths and all stations averaged) and air pressure difference between Trieste and Athens (after Zore-Armanda, 1969, and new data).

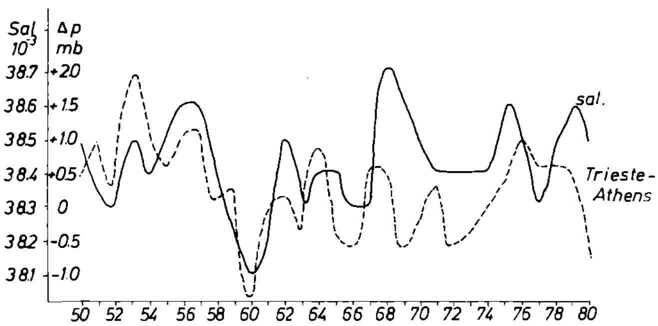


Figure 10.6 Annual average values of sea surface temperature in the middle Adriatic (Split) and of wind index (frequency x strength for N and NE directions) for Hvar; the same for southwestward extension (Irkutsk = zero point) of the centre of the Russian High and for the sea surface covered by ice in km² in the region of 20 nautical miles around Iceland (after Zore-Armanda, 1972).

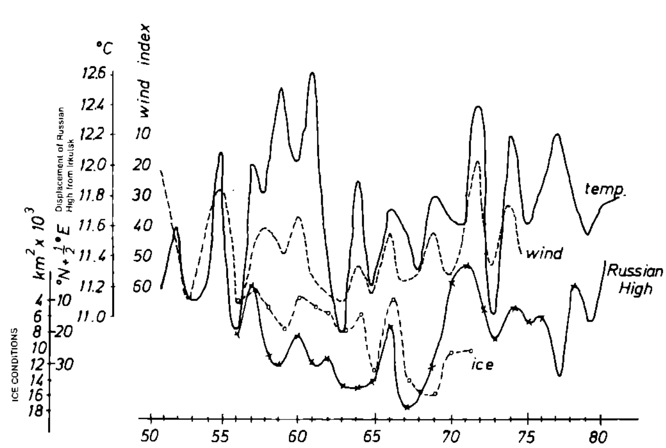


Figure 10.7 Annual values of maximum salinity in the middle Adriatic (Split-Gargano transect), level of primary production in the same area and total fish catch of small pelagic fish of Yugoslavia 3 years later (after Zore-Armanda and Pucher-Petkovic, 1976, and new data).

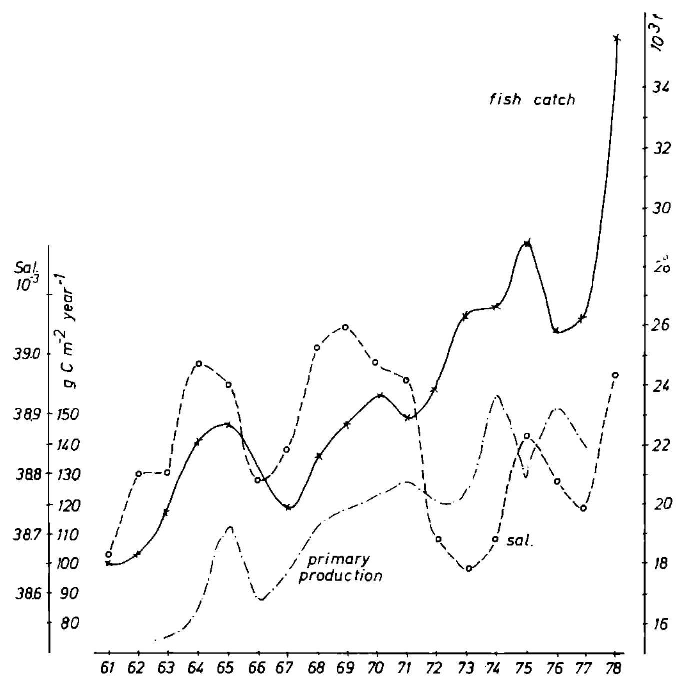


Table 10.1 Correlation coefficients for some parameters in question

	Icelandic Low winter	Russian High winter	Hvar wind winter	^{14}C middle Adriatic	Fish catch Yugoslavia
Icelandic region. Ice conditions	0.42	0.49	0.36	0.34	0.71
Icelandic Low		0.66	0.54	0.68	0.60
Russian High			0.70	0.26	0.26
Hvar Wind				0.49	0.41
^{14}C					0.58

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