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**Time series of ocean measurements**

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# Foreword

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

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

The observational strategy of TOGA is to measure, for a ten-year period, the month-to-month variability of the temperature field and currents in the upper layer of the Tropical oceans in the latitude band 20°N to 20°S. The second large-scale WCRP endeavour, the World Ocean Circulation Experiment (WOCE), will begin later in the decade when oceanographic satellite systems, including at least one altimetric mission, are launched. The

observational strategy for WOCE includes a global suite of in-situ observations for an initial five-year period including tide gauges, hydrography from research ships, expendable bathythermographs from ships of opportunity and drifting buoys. All of the on-going time series projects presented in this volume address the observational requirements of TOGA and WOCE and are assisting scientists in establishing the criteria for the TOGA and WOCE observational strategies. These projects also have the potential of extending TOGA and WOCE, as the representativeness of the discrete ten and five-year experimental periods will be checked against earlier and follow-on data.

The time series volumes are prepared by the Joint IOC/SCOR (Scientific Committee on Oceanic Research) Committee on Climatic Changes and the Ocean (CCCO). This volume was edited for CCCO by Mr. J. Smed, the former Hydrographer of the International Council for the Exploration of the Sea.

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

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

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# 1. Examination of Time Series Data from the Ocean Data Buoys operated by the Japan Meteorological Agency

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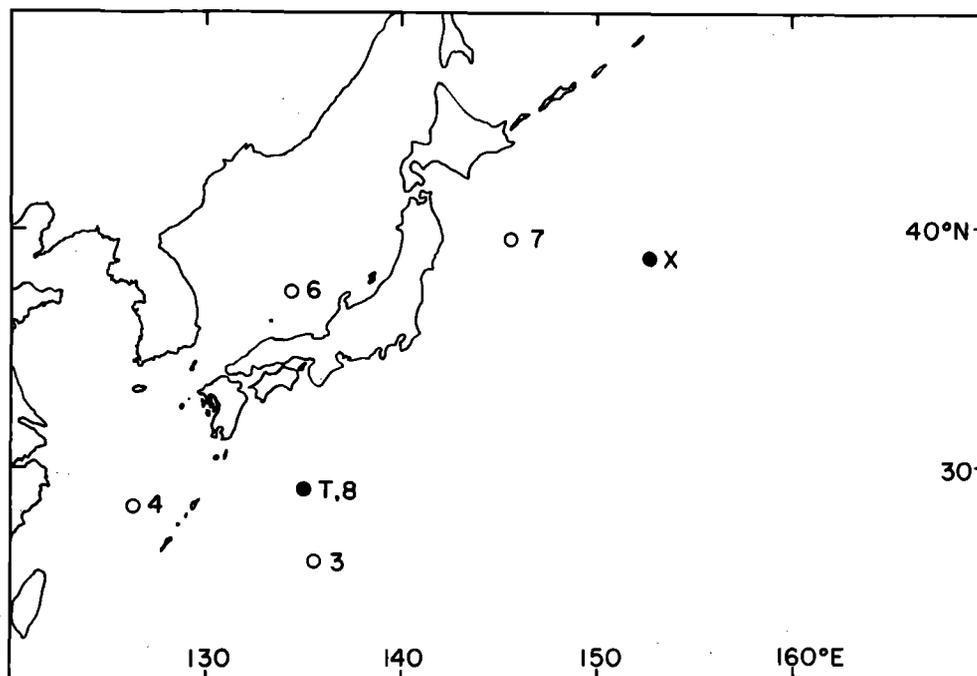
The Japan Meteorological Agency has been operating ocean data buoys since 1972 in order to obtain marine meteorological data in the ocean around Japan, where the available data for the weather forecasting purposes are very few. At present, five buoys are in operation, the locations of which are shown in Fig. 1.1 together with the old Japanese Ocean Weather Stations T and X. Each buoy measures sixteen marine meteorological elements including several surface and subsurface elements such as the water temperature, current velocity and conductivity. The measured data are automatically transmitted every three hours to the Meteorological Satellite Centre at Kiyose near Tokyo and are promptly used for the construction of the weather charts. Afterwards, the collected data are published as "Data from Ocean Data Buoy Stations". Each buoy is scheduled for recovery annually for maintenance of the instruments and the mooring system.

The conductivity and the current velocity data are not available at present because of the difficulty in the maintenance of these sensors. However, we can expect to extract useful information from these data on the uppermost thermal structures of the ocean and their temporal variability. We believe that observing time series

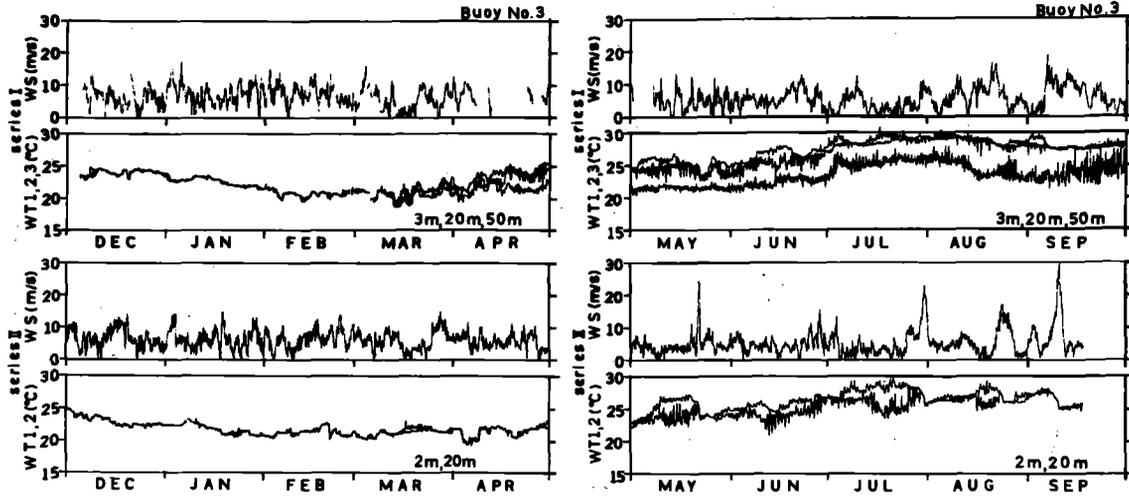
of water temperature and other parameters in detail and clarifying their mutual relationships, is a very important base for further detailed investigation of the upper ocean variability, and for planning upper ocean mixed layer field experiments.

The present short article is a summary of our examination (Yano, Hanawa and Toba, 1984) of the data obtained at the three buoys. Buoy Nos. 3, 4 and 6 are used in the study, of which the locations are  $25^{\circ}45'N$ ,  $135^{\circ}55'E$  (south of Honshu),  $28^{\circ}20'N$ ,  $126^{\circ}05'E$  (east part of the East China Sea) and  $37^{\circ}45'N$ ,  $134^{\circ}23'E$  (the Japan Sea), respectively. Two time series (series I and II) with the length of about one year each were selected for each buoy. Although the water temperatures were usually measured at three depths (abbreviated hereafter as WT1, WT2 and WT3) shallower than 50 m, the depths of sensors were slightly different in each case (at present, sensor depths are fixed at 2, 20 and 50 m for each buoy). After proper corrections and interpolations were made for the data, the time series for water temperature and wind speed were reproduced in Figs. 1.2, 1.3 and 1.4 for Buoys Nos. 3, 4 and 6 respectively. The wind velocity is measured at the buoy platform at the 7.5 m height above the sea surface.

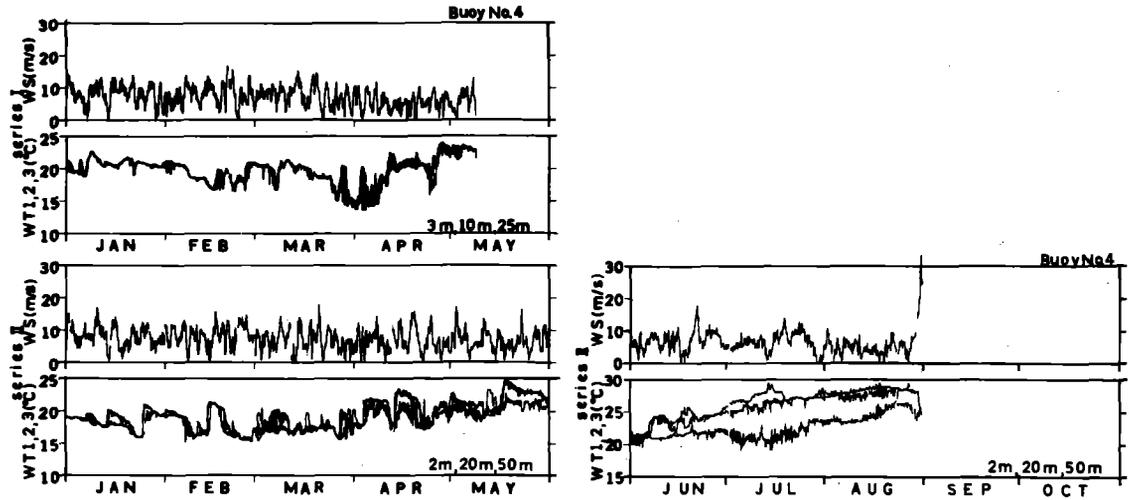
**Figure 1.1** Locations of the Ocean Data Buoy Stations managed by the Japan Meteorological Agency (o) and the old Japanese Ocean Weather Stations (OWS) T and X (•). The Buoy No. 8 is at the same location with the OWS-T.



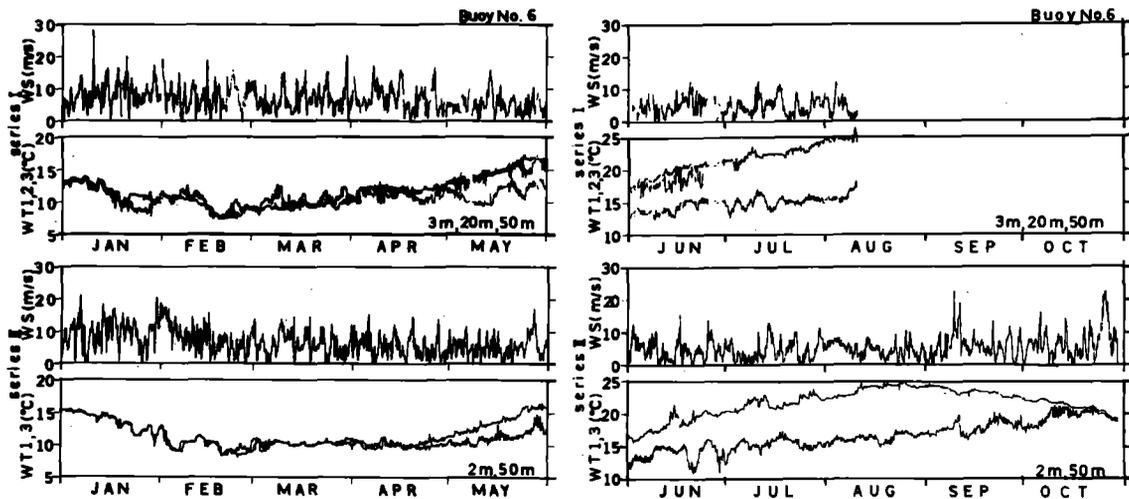
**Figure 1.2.** Time series of wind speed (WS) and water temperatures (WT1, WT2 and WT3, the depths are indicated respectively) at Buoy No. 3 for series I (17 October 1976 - 13 October 1977, upper panels) and series II (26 August 1981 - 17 September 1982, lower panels). Sensor depths are shown in each panel. Note that WT3 (50 m) in series II was not available.



**Figure 1.3.** As in Fig. 1.2 except for Buoy No. 4 (series I: 5 September 1975 - 9 May 1975; series II: 10 October 1980 - 31 August 1981). Note that the depth of water temperature is different between series I and series II.



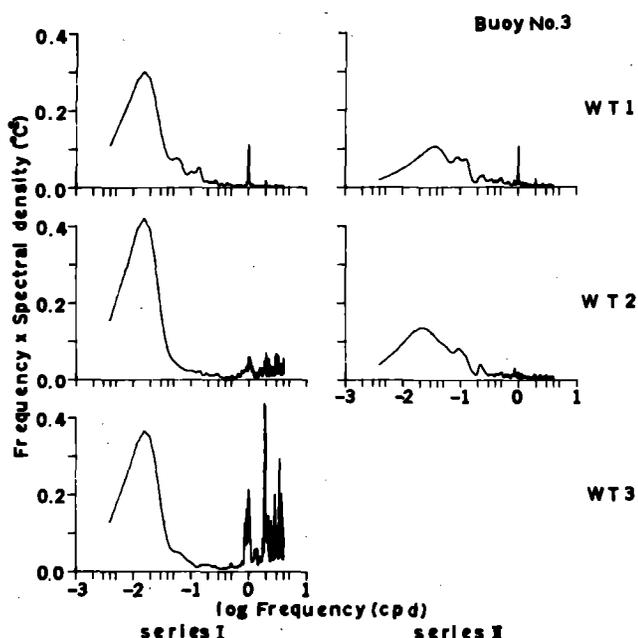
**Figure 1.4.** As in Fig. 1.2., except for Buoy No. 6 (series I: 14 October 1978 - 11 August 1979; series II: 3 November 1979 - 30 October 1980). Note that WT2 (20 m) in series II was not available.



Spectral analyses of water temperature were also made. Figs. 1.5 and 1.6 show the results for Buoy No. 3. Fig. 1.5 shows the result for 2048 observations (256 days) and Fig. 1.6 is a dynamic spectra for approximately two-month sections of the time series each having 512 observations (64 days). Both spectra are plotted as the variance conserving form. Similar results for Buoy Nos. 4 and 6 are shown in Figs. 1.7 and 1.8, and in Figs. 1.9 and 1.10, respectively.

Conclusions extracted by detailed inspection of the above time series and the spectral analyses, together with brief discussion, are as follows.

**Figure 1.5.** Spectra of water temperature at Buoy No. 3 for series I and series II. The periods of each series used to calculate the spectra are 1 May 1977 to 13 October 1977 for series I and 26 August 1981 to 8 May 1982 for series II. Note that the spectra are variance conserving plots. Spectra for only series II were obtained from data in which annual and semi-annual variations were removed.



Passage of different water masses. Every time series of water temperature shows abrupt changes which cannot be explained as the result of the air-sea heat exchange and/or the vertical mixing in the sea. These variations seem to be due to the passage of water masses with sharp fronts. The water masses have various vertical structures and passing time scales, and therefore, spatial scales.

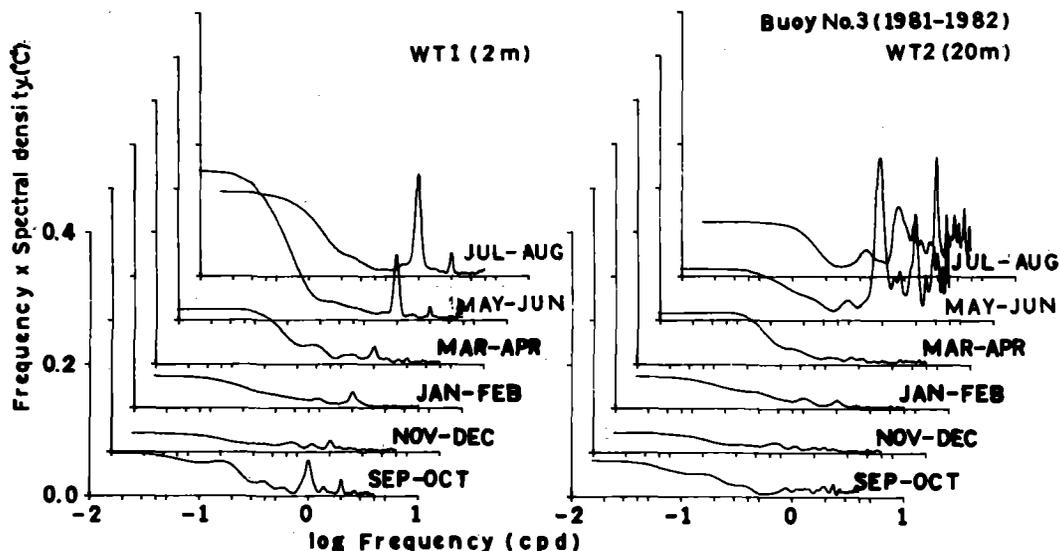
The existence of water masses whose dimensions were not so large as synoptic scale warm or cold eddies was already reported. For example, Kurawata et al. (1983), who analysed the heat budgets of the upper ocean using the data obtained at OWS-I (see Fig. 1.1), pointed out that many water masses existed in this area and that the horizontal transport of heat in the upper ocean was performed by them. Toba et al. (1984) showed the infrared images of the Japan Sea obtained from the NOAA-6 and 7 satellites and calculated the wave number spectra of surface water temperature from them. The images show many eddies of horizontal scales of about 100 km. In addition, a structure like the bands of a spiral nebula in temperature was shown over the eddies; this structure appeared in the spectra of sea surface temperature as a secondary peak around the scale of 15-20 km.

The temperature changes in winter at Buoy No. 4 are the reflection of the interchanging passage of the cold water over the continental shelf of the East China Sea and the warm Kuroshio water, and of the mixture of them with medium temperatures. It is known that the Kuroshio in this area meanders, spins off the eddies and is accompanied by the frontal waves (Huh, 1982; Shibata, 1983).

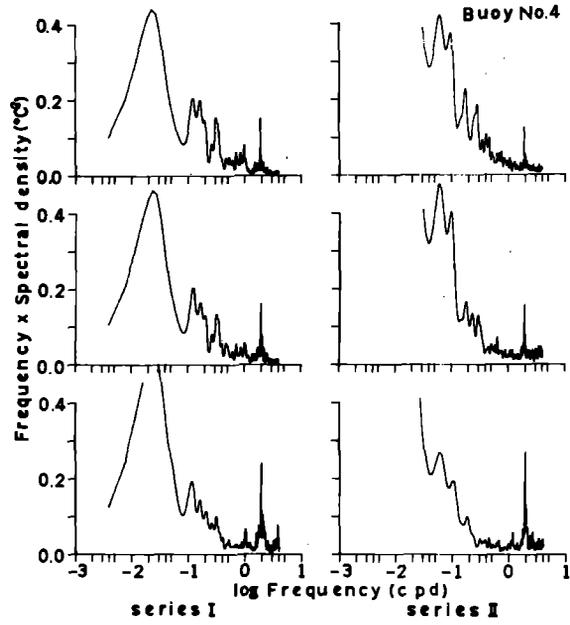
Diurnal variation. During the light wind period in summer, diurnal variations dominate the sea surface temperature, which is clear in spectra of WT1 in Figs. 1.6 and 1.10. Their maximum amplitudes are as much as 0.5°C at Buoy No. 3 while a little smaller at Buoy No. 6 because of the high latitude.

Wind disturbance. Rapid drops in temperature in the upper layer are found in the warming season when the wind is strong. Its temperature reduction has a duration from several days to one week.

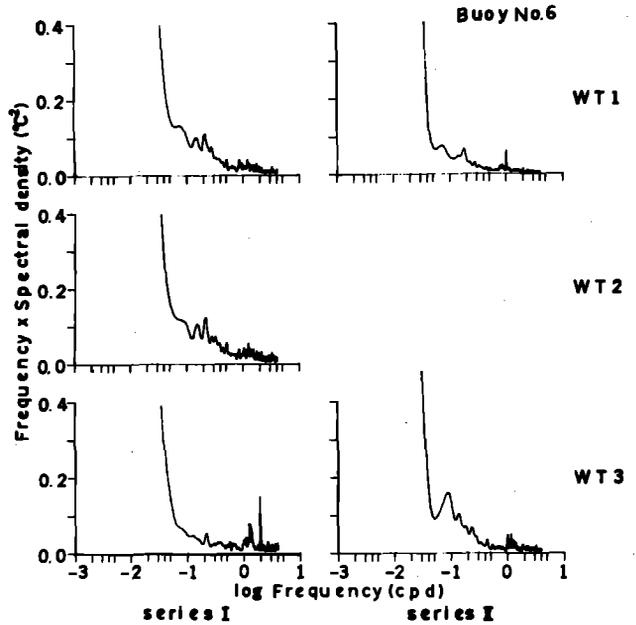
**Figure 1.6.** Evolution of spectra of water temperature at Buoy No. 3 for series II. Spectra are obtained from about two months of data in which the linear trend was removed. Note that the spectra are also variance conserving plots.



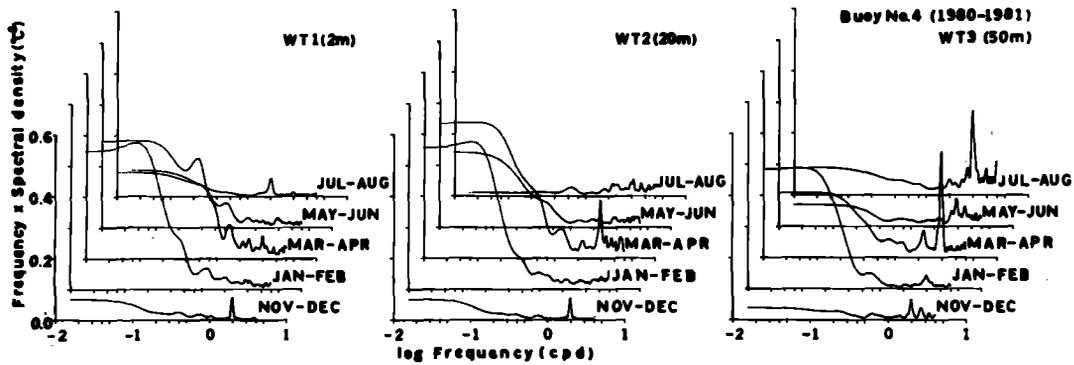
**Figure 1.7.** As in Fig. 1.5., except for Buoy No. 4 (periods used are 1 December 1974 to 9 May 1975 for series I and 19 October 1980 to 2 July 1981 for series II).



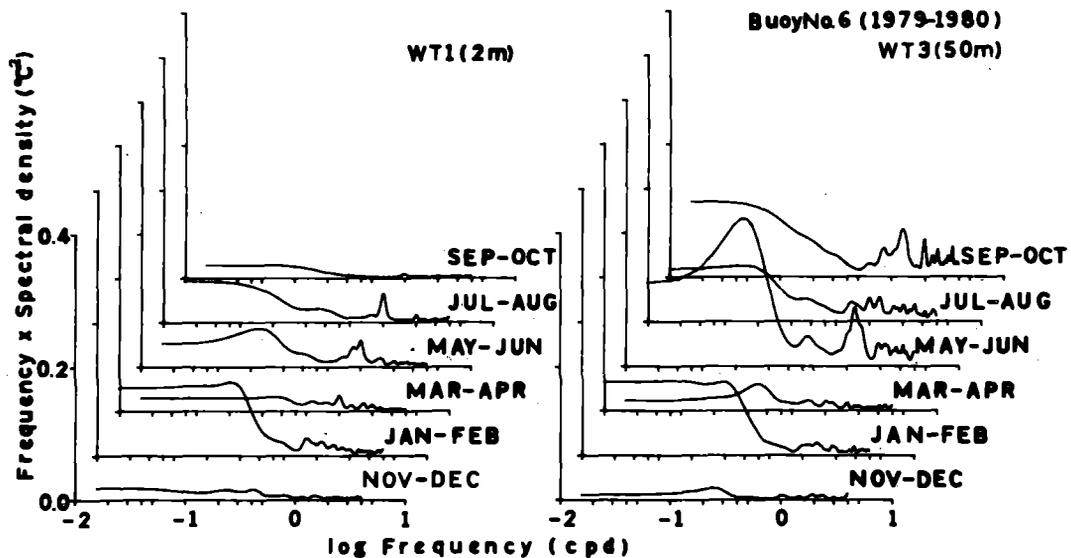
**Figure 1.9** As in Fig. 1.5., except for Buoy No. 6 (periods used are 14 October 1978 to 30 April 1979 for series I and 3 November 1979 to 15 July 1980 for series II).



**Figure 1.8.** As in Fig. 1.6., except for series II of Buoy No. 4.



**Figure 1.10** As in Fig. 1.6., except for series II of Buoy No. 6.



In the lower layer, however, there are great variations which are not directly associated with storm events. At Buoy No. 6, after the storm events, there are sometimes variations of near-inertial periods in the lower layer. The peak near one day in the spectra of WT2 in Fig. 1.10 may correspond to these variations, which are considered as the manifestation of the downward propagation of inertial gravity waves.

Tidal effect. Semi-diurnal variations are dominant in the thermocline below the mixed layer at Buoy No. 3, as is clearly shown in spectra of WT2 in Fig. 1.6; this seems to be the internal tide. It was also found that there were abrupt

changes of phase of semidiurnal tide in the temperature records. At Buoy No. 4 there are temperature variations which are caused by tidal excursion in the whole layer of the upper 50 m, i.e., due to the barotropic tidal current, as inferred from Fig. 1.7.

As already mentioned, data obtained by buoys only may not be sufficient for the consideration of the upper ocean phenomena. However, the combination of the routinely available buoy data and infrared images obtained at the same time within the wide area, will be very valuable for the understanding of upper ocean physics.

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## 2. Satellite Drifters Northwest of Australia

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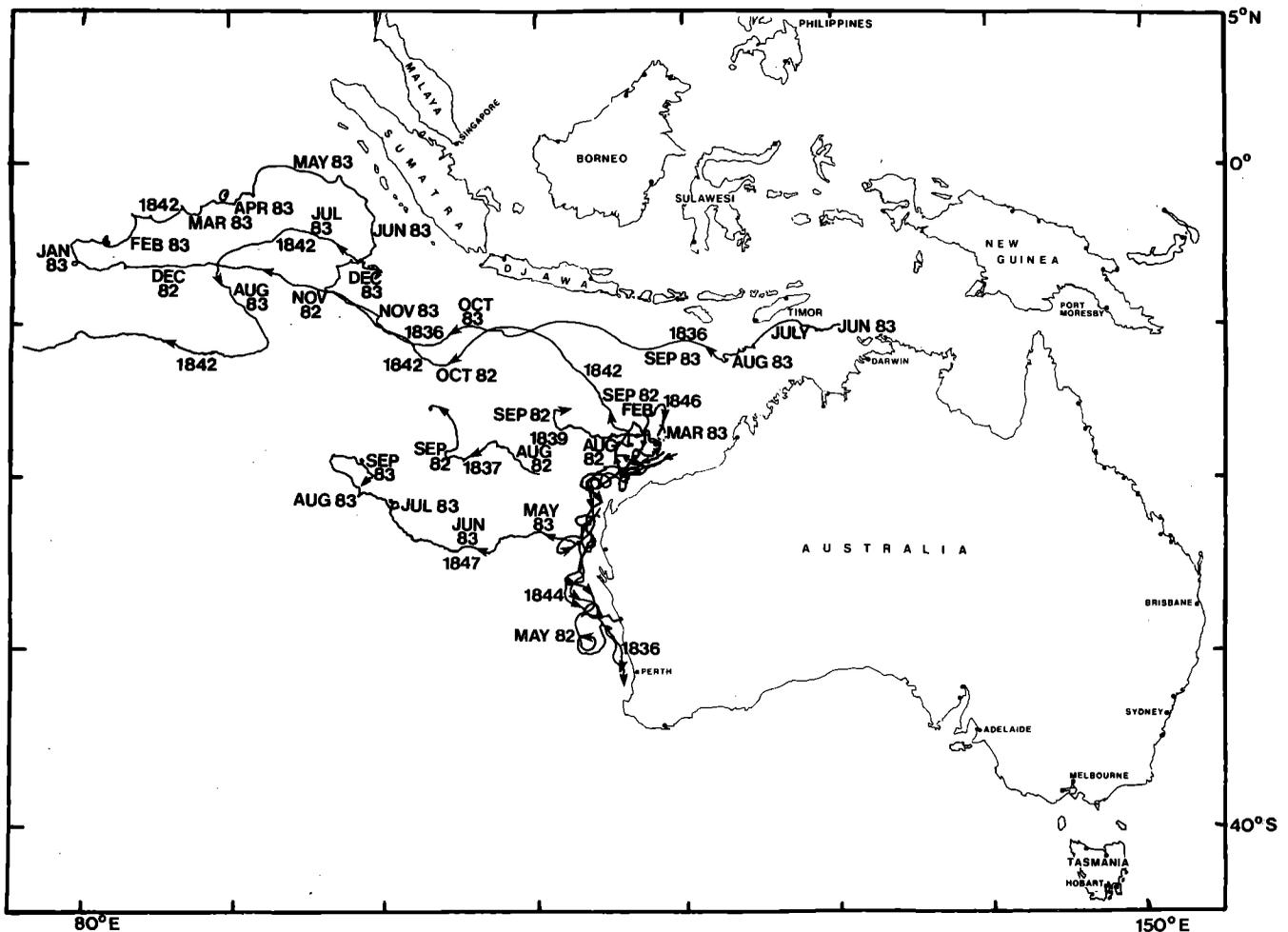
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In 1982 and 1983 a dozen drifter releases were made on and near the continental shelf north and northwest of Australia. At that time the CSIRO Division of Fisheries Research was conducting a survey of the resources of the region. Some lines of Nansen stations were occupied on each bi-monthly survey. The drifters were torpedo-shaped and were drogued with a parachute at 20 metres (Cresswell, Richardson, Wood and Watts, 1979).

The continental shelf and slope northwest of Australia was seen from the drifter data (Fig.

2.1) to be a source area for the Leeuwin Current flowing to the south and the South Equatorial Current flowing to the west. The source for the region itself was less apparent; a drifter (1836) released north of Darwin in May 1983 may support the suggestion of flow through the Indonesian archipelago from the north. Note that not very much net flow is expected through the shallow Torres Strait between northern Queensland and Papua New Guinea. The Darwin drifter closely followed the track made by another (1842) one year earlier.

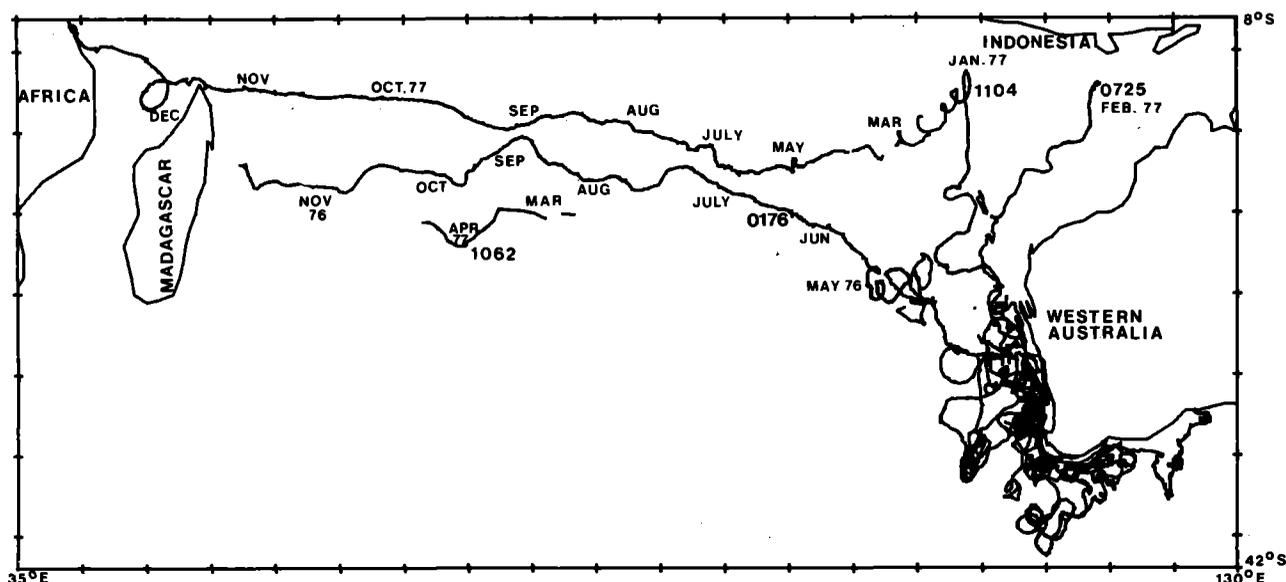
Figure 2.1. The tracks of drifters released north and northwest of Australia in 1982/83



The general trend of westward flow in the region, at least away from the continental shelf and slope, can be compared with earlier drifter tracks (Fig. 2.2, Cresswell and Golding, 1979). At that time, except for drifter number 1062 released at 11°S, 105°E, the releases took place in a study area between 29° and 32°S on the continental shelf and slope. Drifter 1062 moved westward in the South Equatorial Current and three drifters, 0176, 0725 and 1104 escaped to the north from the study area. Of these, 0176 then moved off to the west. Drifter 1104 moved north to about 12°S where it apparently entered a cyclonic eddy being advected westward. After two months 1104 escaped from the eddy and was carried westward in the South Equatorial Current. Drifter 0725 moved north eastward until it ran aground on a reef southwest of Timor.

It would appear then that the behaviour of the 1976/77 and 1982/83 drifters were similar to the extent that both the South Equatorial Current and the Leeuwin Current were dominant influences. However, only in 1976/77 were there clear examples of northerly and northeasterly flow. The reason for disagreement may be that the seasonal signal is such that only the 1976/77 drifters were in the right place to respond to it. Alternatively, the El Niño/Southern Oscillation event of 1982/83 may have been involved. It would be most interesting to periodically release one or more drifters between, say, Bali in Indonesia and Derby in Western Australia.

**Figure 2.2.** The tracks of drifters released in a study area on and near the continental shelf between 29° and 32° S in 1976/77.



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### 3. Time Series of Ocean Data: Their Use in Offshore Engineering

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Snamprogetti's Offshore Division undertakes engineering activities in the field of offshore structures, submarine pipelines and coastal interventions. The projects vary from feasibility studies to detailed engineering for construction. The technology involved in offshore engineering requires a continuous up-dating of project criteria and methodologies and a progressive improvement of environmental information and mathematical tools. The ever-increasing demand for reliability has consequently promoted oceanographic activity. In early 1976 a group of specialists in physical oceanography was set up, to analyse and study the physical aspects of the marine environment relevant to submarine pipelines, to offshore and coastal structures and to coastal management plans.

In connection with engineering problems, the following activities are usually undertaken:

- oceanographic surveys
- statistical data processing
- phenomenological analysis, and modelling
- estimate of extreme values of relevant physical parameters.

For the accomplishment of such a task, the availability of long time series of physical parameters (waves, currents, wind and atmospheric pressure, temperature and salinity, etc.) is considered a fundamental element for the phenomenological analysis of the dynamical processes, for the calibration of the models, for correlation with forcing meteorological terms, etc. As a consequence, extensive surveys of wind, waves and currents are usually carried out in the framework of the various projects. The experience to date of Snamprogetti is composed of the Sicily Channel, the North Sea and Norwegian Trench, the Persian Gulf, the Magellan Strait, the Cambay Bay in the coastal area of western India and the Adriatic Sea.

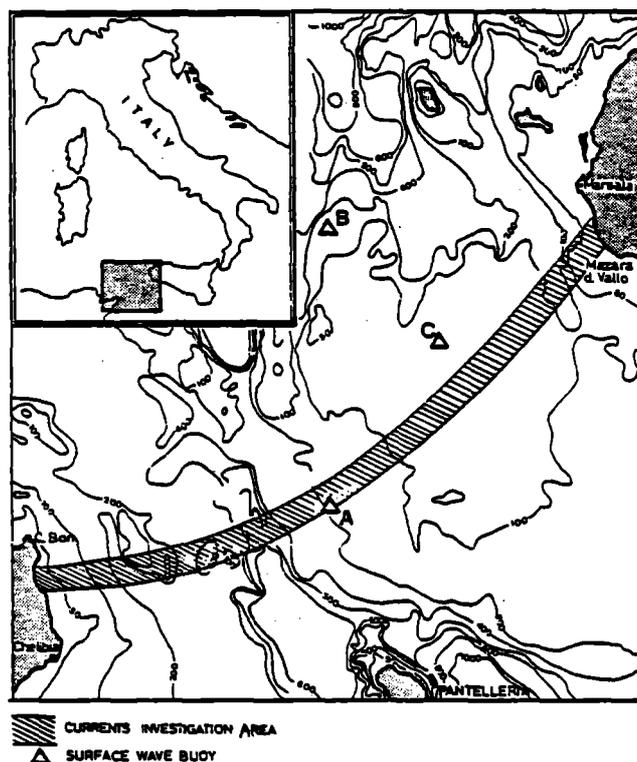
Long-term time series are submitted to statistical processing which usually involves spectral, filtering, harmonic, multi-variate regression analysis, etc. In some cases, simulation modelling of hydrodynamical phenomena and of surface wave generation and propagation has been applied to extend the information to the whole area of interest, and/or to hindcast past extreme events. A brief analysis of the data available and of the relevant results obtained during the oceanographic studies is given below. Though the results presented are restricted to the Sicily Channel, a brief remark about data availability and experience in other areas is put forward. A complete description of the results can be obtained from the Technical Reports listed in References.

#### Hydrodynamics of the Sicily Channel and Adjacent Waters

During two different pipeline projects (Sicily Channel Crossing and Sicily-Libya Crossing) a large set of experimental data of wind, waves and currents was collected during 1976-1977 and 1981-1982, respectively (Fig. 3.1.). The survey activity, carried out by OGS of Trieste under Snamprogetti's supervision (OGS, 1978; Snamprogetti, 1983), involved:

- wave measurements by Datawell Buoys (9 stations)
- wind and wave measurements in open sea (depth 400 m) by Hermes buoy
- current measurements by NBA current meters (11 stations in the Sicily Channel, 9 stations in the Maltese area; about 20 current meters employed simultaneously)
- vertical current profiles by Neil Brown profiler, mainly in coastal areas.

Figure 3.1 Snamprogetti experimental data collection area, 1976-1977 and 1981-1982.



All data stored in the data bank, on a 3033 computer, have been processed by the Snamprogetti TEMAR/FISA Group (Snamprogetti, 1979a,b) with the aim of attaining the following information:

- type and intensity of currents, their space and time variability
- statistical properties of the wave field
- space and time variability of the wave climate
- extreme conditions of waves and currents.

The analysis of the current has been undertaken in terms of steady ( $E_M$ ) and eddy ( $E_{EDDY}$ ) kinetic energies (Fig.3.2.), using filters to separate the different components (Gracini and Michelato, 1983). This analysis has confirmed the well-known long-term regime, but has also shown a large variability of the current, occurring at different time scales. In the Sicily Channel, this variability is partially due to tidal oscillations,

diurnal and semi-diurnal, which are stronger over the continental shelf and the Sicilian coastal area than in the Tunisian and deep areas (Fig. 3.3.). Moreover, remarkable low-frequency components, probably driven by meteorological forces, have also been found trapped at both coastal zones (Fig. 3.4.). Typical periods merge from 10 - 15 days. In the area between Sicily and Libya tidal currents prevail only on the continental shelf, between Malta and the coast of Sicily. They are negligible in the offshore area.

On the other hand, a very intense residual current flowing south eastward has been recorded in the surface layer along the Sicilian coast. The surface layer is usually affected by very strong inertial oscillations ( $> 40$  cm/s), which intensify during summer (Fig.3.5.). This phenomenon is not coherent across the section and generally is not experienced across the Sicily Channel, as confirmed in Fig. 3.3. where the energy peak at inertial frequency is lacking.

**Figure 3.2.** Distribution of mean energy  $E_M$  and eddy energy  $E_{EDDY}$  across the Sicily Channel, as found from experimental data. The relative role of steady and fluctuating currents is expressed by the distribution of the ratio  $E_M/E_{EDDY}$ .

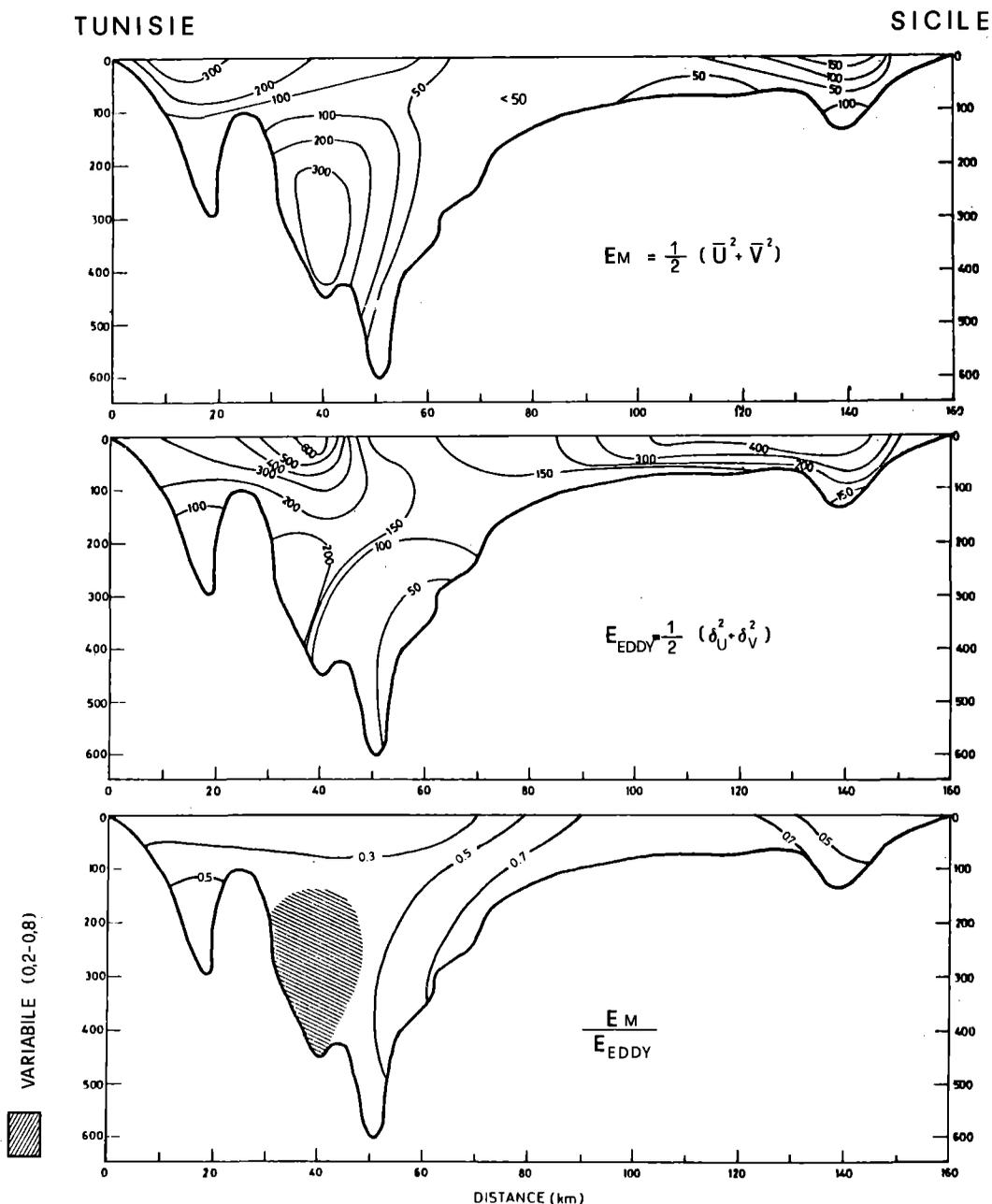


Figure 3.3. Current spectra in the Sicily Channel.

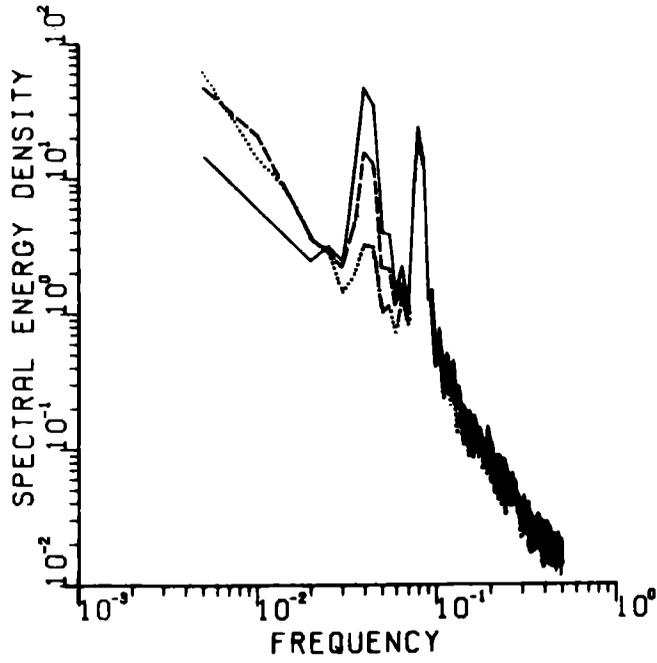


Figure 3.5. Current spectra in the offshore Libyan area.

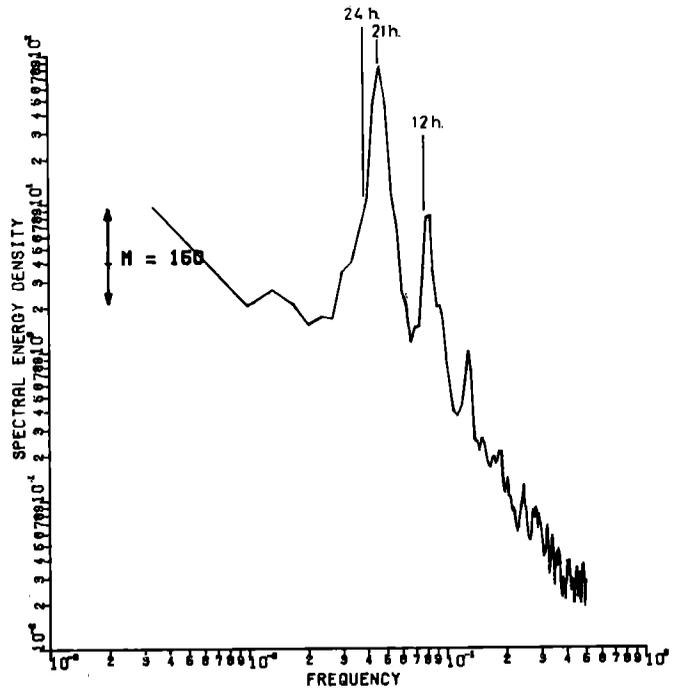
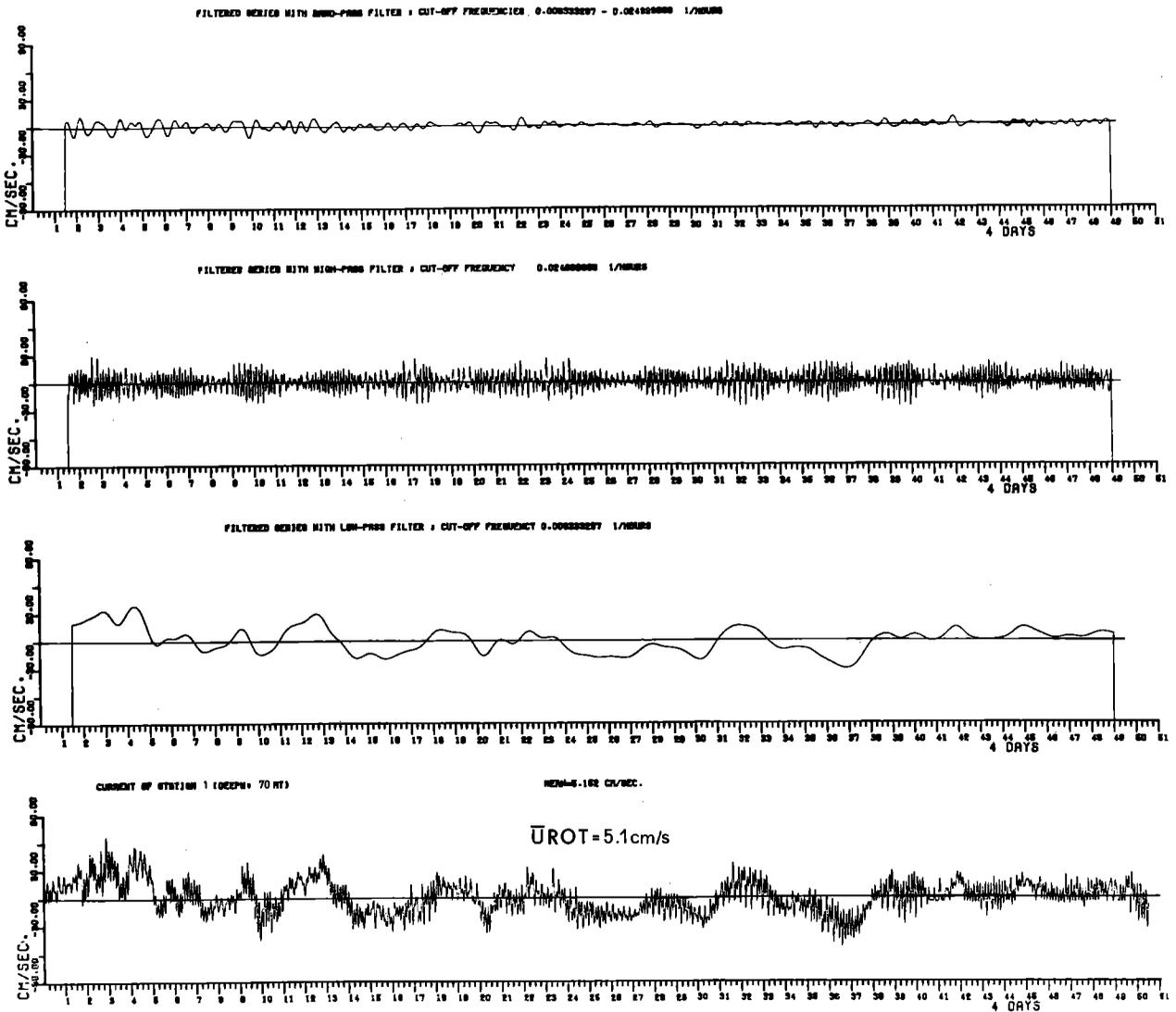


Figure 3.4. Filtering analysis of a long time series of current data measured in the Sicily Channel (Tunisian coastal area). Current components corresponding to stormy events, tidal effects and long-term adjustments are obtained by band pass (2-5 days), high pass (< 2 days) and low pass (> 5 days) numerical filters.



As far as wave conditions are concerned, the availability of long series of wave data in the offshore area has allowed the development of the following aspects:

- statistical correlation among different parameters
- single wave statistics
- wave spectral distribution and shape analysis
- calibration of wind-wave models
- hindcasting of storm waves that actually occurred in the past.

During the survey, storm waves of significant wave height  $H_s > 7m$  have been recorded repeatedly, with maximum waves attaining 12 m, events which are strictly correlated with the cyclogenesis in the lee of the Alps (Grancini et al., 1983). During these storms for which the wave spectrum evolution is shown in Fig. 3.6, the energy density distribution fits very well with a JONSWAP spectrum (Fig. 3.7) so that the applicability of a parametric model has been proved suitable (Grancini et al., 1979a). Hindcasting of extreme conditions has been developed for the Sicily Channel and the Maltese area by using a parametric model (Cavaleri et al., 1983), coupled with a wind model (Grancini et al., 1979b) extended over the whole Tyrrhenian Sea. An example of the wind field and wave height ( $H_s$ ) distribution is reported in Fig. 3.8.

Figure 3.6. Prospective three-dimensional view of the wave spectrum time evolution during a two-day stormy event, recorded in the Sicily Channel.

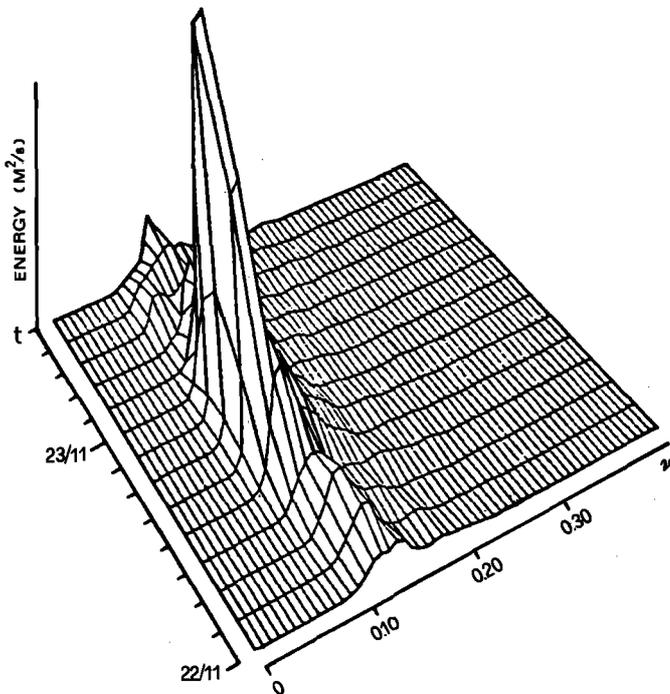


Figure 3.7. Parameterization of wave spectral distribution  $S(f)$  by a JONSWAP spectrum.

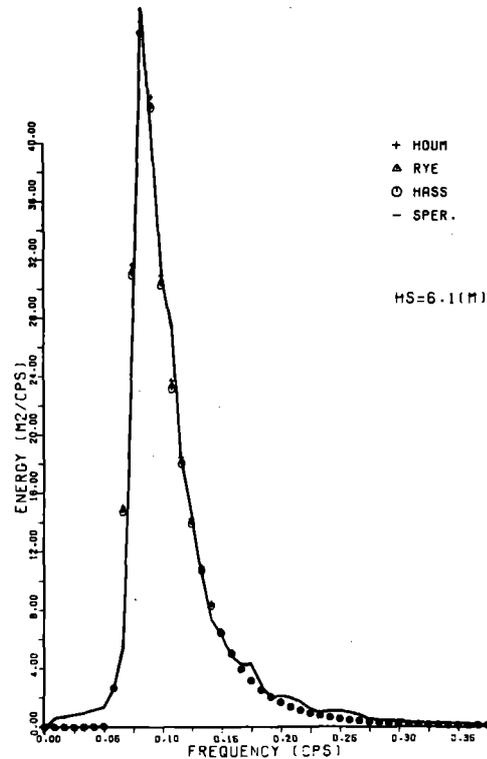
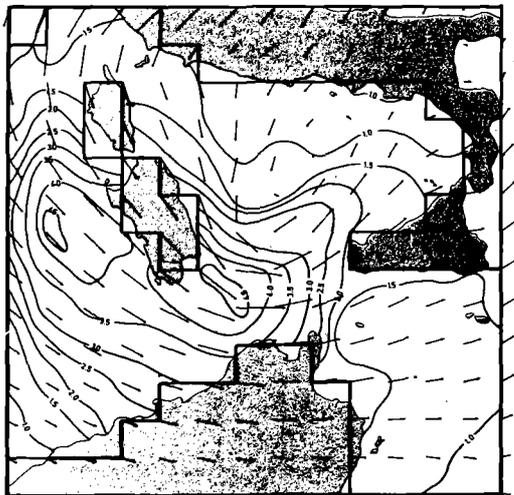
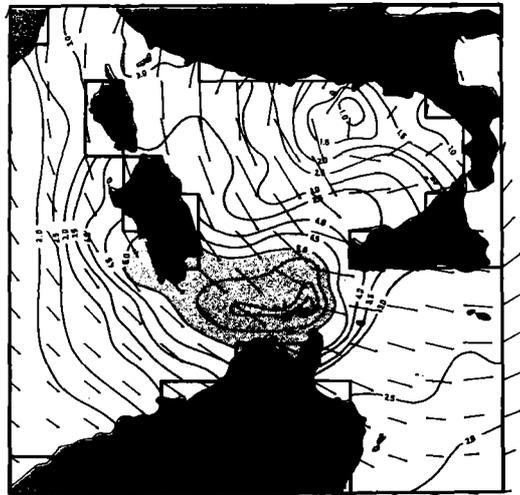


Figure 3.8. Computer hindcasting of the wind and wave fields over the Tyrrhenian Sea, by numerical model.

12.00 HRS - DEC. 30, 1974



18.00 HRS - DEC. 30, 1974



A set of storms that actually occurred during the last 30 years (1950-1980) has been extracted from a larger sample of events and has been stratified according to meteorological criteria, to obtain homogeneous samples. The wind and wave models have been calibrated on the basis of experimental data and then run on a set of about 80 events, to get a reliable sample population for extreme statistics.

## Coastal Dynamics of the Adriatic Sea

The progressive coastal erosion experienced along the Italian coast of the Adriatic Sea since the early 1970s compelled regional authorities to develop a general plan of coastal protection. The planning started in early 1980 with a general study of the physical and geomorphological aspects, and this involved the Emilia-Romagna, Marche and Abruzzo coasts. The aim of the study was to attain an understanding of the coastal dynamics at regional and subregional scales in order to identify critical areas and to determine proper strategies of intervention. The environmental study had the following objectives:

- to assemble and organize existing data and information
- to identify the physiographic area
- to estimate the role of different factors controlling the coastal dynamics for each area
- to develop a sediment budget analysis
- to provide an estimate of the trend of coastal erosion problems.

The general activity has involved the installation of a network of gauges to record tidal oscillations and storm surges along the coast, and the installation of four offshore automatic stations (approx. 30 m water depth) to measure waves and meteorological parameters over a long time.

Snamprogetti's activity has mainly concerned the analysis of meteorological and oceanographic aspects. In particular, offshore and coastal wave climates have been estimated in order to assess the littoral transport regime and to identify zones of convergence and divergence along the coast. Results have shown a qualitative accordance with those obtained from the sedimentological and cartographic analyses. Because of the shallowness of the water the coastal wave climates have been calculated by taking into account the refraction, shoaling and dissipation processes up to breaking conditions. A model has been used to introduce the actual bottom topography and the frequency of occurrence of any element of the offshore wave climate. Emphasis has also been laid on the flooding phenomenon which can occur in the northern part of the Adriatic Sea. Long time series (> 10 years) of sea level and wave height have been analysed to estimate the combined action of storm surge and wave set up which can produce very high water levels along the shore. Extreme conditions of the joint occurrence have been computed by statistical methods, to get a risk estimate of each level exceedence.

## Dynamics of the Magellan Strait

An investigation of the hydrodynamical phenomena that occur in the Atlantic section of the Magellan Strait was undertaken by measuring sea surface oscillations and currents at different sites for rather long periods, during 1978-1979. A detailed study of the time series was carried out with spectral and cross correlation techniques and harmonic analysis. Results have demonstrated that the dynamics are completely dominated by the propagation of the semi-diurnal tidal component and its higher harmonics which generate strong currents (3-4 m/s) in the First and Second Narrows.

To extend the dynamical information to the whole basin, a two dimensional hydrodynamical model valid for shallow waters and including advective terms was used. Calibration was carried out in terms of the  $M_2$ ,  $M_4$  and  $M_6$  tidal components, whose boundary conditions were taken from experimental data. The comparison of the calculated values with the experimental ones for surface elevation and current was very successful and the  $M_2$  tidal harmonic has been reproduced at the beginning (P. Delgada) and at the end (P. Satellite) of the First Narrow with less than 3% error. The current pattern off the narrows is dominated by the jet-like structure of the flow and by the bottom topography. Due to the large amplitudes of the tidal wave at the Atlantic entrance (5m), shallow areas are alternatively flooded and laid free and this effect is correctly accounted for by the model.

## Dynamics of the Persian Gulf

An investigation of the dynamics of the Persian Gulf has been undertaken using experimental data and numerical modelling. The availability of current meter time series at different stations and depths in the northern part of the Gulf has clarified some aspects of the tidal dynamics. The dominant current is represented by semi-diurnal and diurnal tidal components whose amplitudes change considerably along the basin, giving rise to a rather complex pattern. Coupling of the wind stress with the very intense vertical stratification (two-layer system) generates a further complexity of the current pattern. Indeed internal waves at quasi-inertial frequencies arise in the offshore area, and vertical oscillations of the interface and rotary currents are experienced which are in counter phase in the upper and lower layer. The inertial frequency is very close to the diurnal tidal frequency and this makes separation of the components rather difficult. A two-dimensional HN model has been developed to identify the areas of stronger tidal currents. Calibration was carried out in terms of the  $M_2$  and  $K_1$  components of sea level oscillation at coastal stations, and of currents at coastal and offshore stations. The two-layer model is now operating and its application for scientific purposes is underway.

## Dynamics of the Gulf of Cambay (Bombay)

A detailed study of the oceanographical conditions in the Gulf of Cambay was undertaken in 1982 to evaluate the extreme dynamic loads affecting a

submarine pipeline, in order to assure its bottom stability during laying and life. Design conditions along the pipeline routes were estimated in correspondence with typical seasons (NE monsoon, SW monsoon, cyclonic periods). Particular emphasis was given to the analysis of the extreme wave conditions expected during cyclones. Consequently, available information concerning the cyclone features (pressure drop, radius, track, duration) and cyclone statistics in the Arabian Sea (occurrence and return periods) was collected and analysed. Analysis of the current pattern existing during the monsoon and cyclonic seasons was also undertaken by an experimental survey. Long time series of current, representative of the dynamical regime during typical seasons, are available for various places.

The area is mainly affected by strong tidal currents ( $> 1.5$  m/s) and very small residual currents ( $< 10$  cm/s), except during cyclone events. To get an estimate of wind-driven currents in shallow waters, a cyclonic wind model was tested with data collected during an intense cyclone occurring in November 1982. Furthermore an HN model was applied to a large area in front of Bombay and a nested model was used to obtain a more detailed analysis of the storm surge (approx. 3 m high) and currents (approx. 1 m/s) in coastal areas.

## Conclusion

The offshore engineering activity of Snamprogetti has led to the establishment of a group of physical oceanographers who are involved in the assessment of the environmental design conditions. The availability of time series of wind, waves and currents is considered a fundamental element of a methodological approach which also involves statistical data processing and simulation modelling. As previously mentioned, technical activity has been developed in different areas. However, the database available for the Sicily Channel represents a new and impressive source of information which can contribute much to the knowledge of the dynamical features of this section which control the large-scale circulation phenomena of the whole Mediterranean Sea. Very promising programmes have recently been proposed by international organizations to analyse the dynamical processes of the eastern and western Mediterranean basins. In both cases the Sicily Channel dynamics must be considered a very important controlling factor. Due to technical and budgetary problems the survey activity will have to be planned in such a way that maximum benefit can be derived from it.

In this connection, the existing data base will be very useful for providing a better definition of the problems. Snamprogetti is open to co-operation with the purpose of obtaining a better knowledge of the dynamical processes across the Sicily Channel.

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## 4. Some Results from a Monitoring Programme in the Drake Passage

R.D. Pillsbury

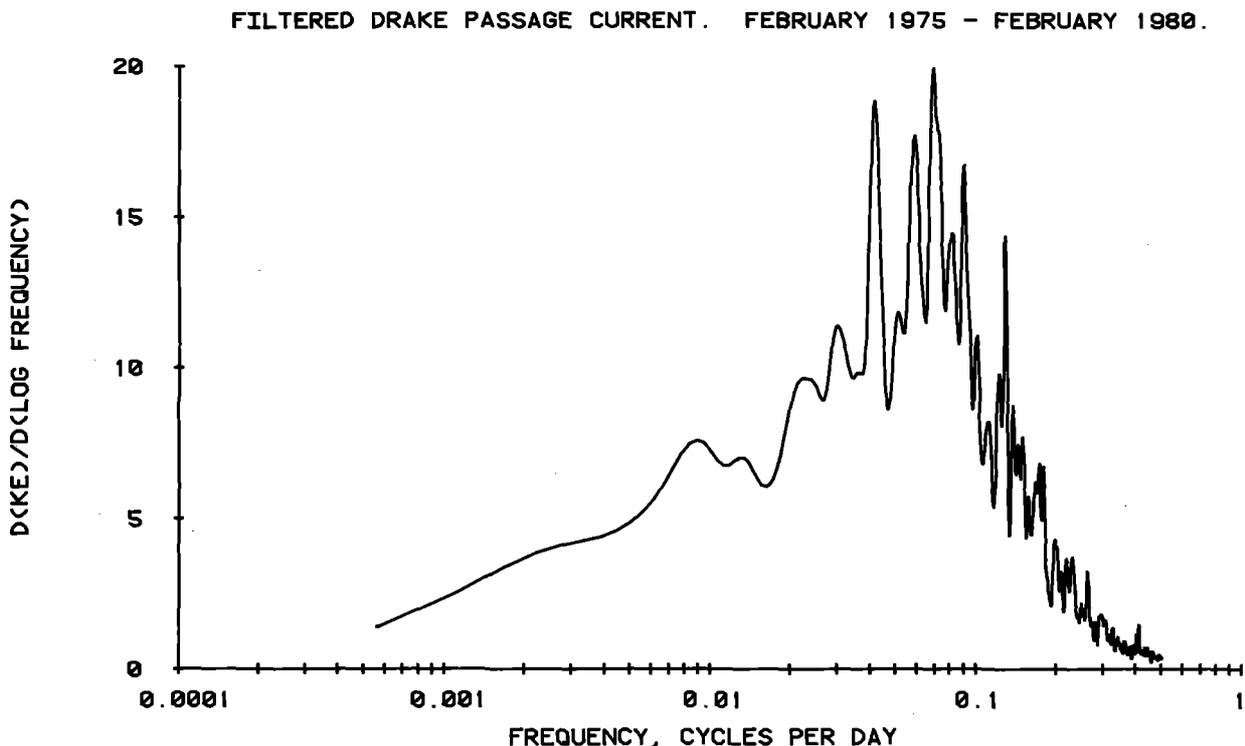
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In the summer of 1972, a U.S.A. National Academy of Sciences Ad-Hoc Working Group on Antarctic Oceanography met to consider the request from the National Science Foundation to the Committee on Polar Research for the production of a research plan for the Antarctic which was to include a 10-year plan of investigation. The resulting document (Ad-Hoc Working Group on Antarctic Oceanography, 1974) emphasized the need for a measurement programme to study the large-scale dynamics and kinematics of the Antarctic Circumpolar Current and its role in the general circulation. Under such a broad charge, the International Southern Ocean Studies (ISOS) programme was started and its data collection effort lasted several years. The data collection period was planned to be coincident with the First GARP Global Experiment (FGGE) when enhanced wind field data would be available. This paper focusses primarily on the data collected by three participating United States institutions, Texas A&M University, Oregon State University and the University of Washington. The intent is not to slight the portions of the programme not discussed but to concentrate on those with which I am most acquainted.

These three institutions each undertook a separate portion of the data collection programme. Oregon State University collected moored current and temperature data, Texas A&M University collected hydrographic data and the University of Washington collected deep-sea pressure data. All of the data sets were used to estimate the time and space scales of motion in the Drake Passage. These three data sets were also used to determine the volume of the Antarctic Circumpolar Current (Whitworth, 1983).

The data were collected over a five-year period. Not all of the data sets were planned to be continuous for the entire period. There was a continuous data set from current meter moorings placed near the Passage. The spectrum of that mooring is shown in Fig. 4.1. It is interesting to note that the spectrum is most energetic in the range of 10-to-50 day periods. The question of how representative this might be in other places in the Circumpolar Current is partially answered by the fact that spectra from the Circumpolar Current south and east of New Zealand show most of the energy to be in the range of 80 days and longer (Bryden and Heath, 1984).

*Figure 4.1 Kinetic energy spectra for the 1817-day record in the central Drake Passage.*



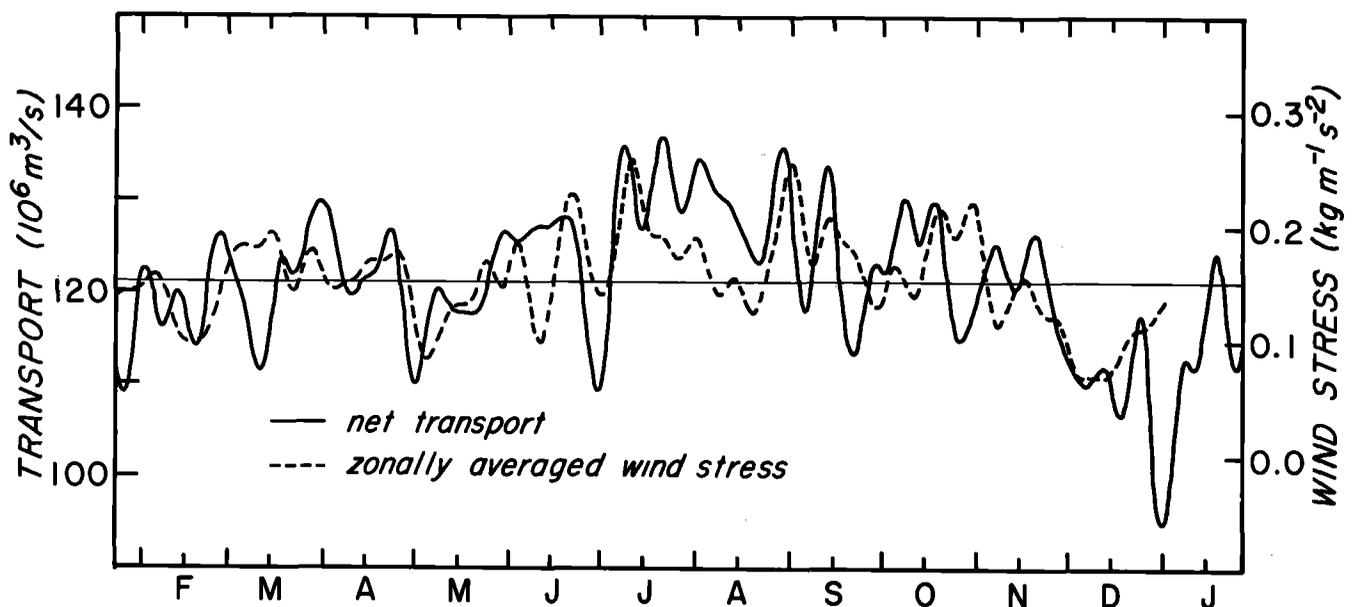
In the original planning, the central mooring was to be in the Antarctic Circumpolar Current and to monitor the flow of that current. As incoming data were analysed, it was evident that such a simple picture of the circumpolar flow and the techniques to monitor it were wrong. The flow is divided into three high-speed cores associated with fronts which separate four distinct water mass zones (Nowlin et al., 1977). The fronts are narrow (Nowlin and Clifford, 1982) and meander up to 100 km from their mean position (Whitworth, 1980). All of these factors make the monitoring of the volume transport of the Antarctic Circumpolar Current a difficult task using mooring alone.

The combination of hydrography and moored instrumentation can be used to monitor the flow.

The final experiment in the Drake Passage was called Drake 79. The monitoring results from that experiment are discussed in detail by Whitworth (1983). The net transport through the Drake Passage and the zonally averaged eastward component of wind stress between 43° S and 65° S are shown in Fig. 4.2.

The complexity of the ISOS data sets makes simple descriptions difficult and potentially misleading. Recently analysed satellite data indicate that at least the temporal variability of the flow may be studied from space (Fu and Chelton, 1984). It is hoped that monitoring of important regions of the world's oceans can benefit from the experience gained in the ISOS programme.

**Figure 4.2.** The net transport through Drake Passage and the zonally averaged eastward component of wind stress between 43° and 65° S. Both series have been smoothed with a 10-day low-pass filter. (From Whitworth, 1983).



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# 5. Hydrographic Evidence for Seasonal and Secular Change in the Gulf Stream

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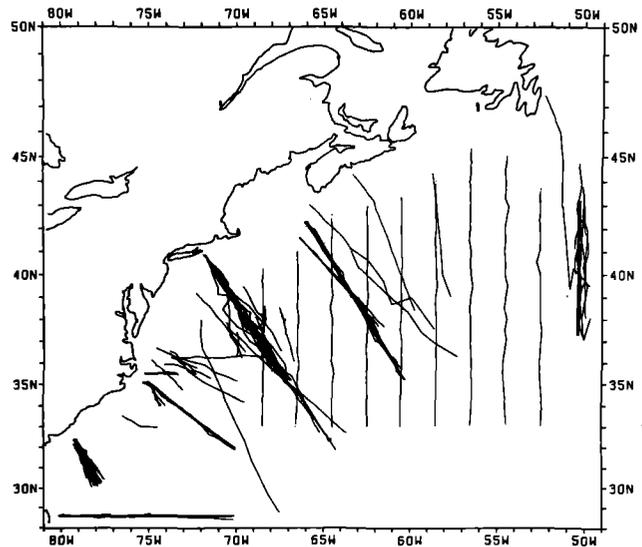
## Introduction

This note is a sequel to a report on the Gulf Stream that was prepared for the Time Series of Ocean Measurements meeting in Tokyo in May 1981 (Rossby, 1981). That report was essentially a brief review and summary of earlier studies of the temporal variability of the Gulf Stream, the most noteworthy of which were the Nova University studies of transport by the Florida Current (Niiler and Richardson, 1973) and Worthington's (1976) summary of 30 hydrographic sections between the U.S.A. and Bermuda. To our knowledge no other systematic analysis of the many other Nansen cast sections across the Stream has ever been attempted. This note discusses our efforts to do so. In particular we are interested in the spatial and temporal variability of the instantaneous Gulf Stream, specifically the dynamic height field east of Cape Hatteras. We compare our hydrographic estimates of dynamic height difference across the Stream with direct measurements of transport and with satellite altimetry. We also look for evidence of change between the late 1930s (Iselin, 1940) and the post-World War II period.

## The Data Base

In 1982 we reviewed the published literature, checked data reports and scanned various cruise summaries from the U.S.A. National Oceanographic Data Center (NODC) to locate as many hydrographic sections across the Gulf Stream as possible. These data were obtained from NODC and archived without change in format. An index file was constructed to identify the hydrographic stations which make up a section, and, as best as we could, the two stations that best delimit the Slope Water and Sargasso Sea edges of the Stream. A technical report (Mazzarelli and Rossby, 1983) describing the data base, the index file and some software to facilitate data retrieval is available. Fig. 5.1 shows most of the 157 sections we have been able to locate thus far. The sections near 70°W are the most extensive in time with sixteen sections from before World War II. The majority of those were taken by investigators at the Woods Hole Oceanographic Institution. The dense sets at 29°N, 34°N, 65°W and 50°W were standard U.S. Coast Guard Sections (discontinued). The set at 79°W consists of 27 sections taken biweekly for a period of a year in 1966-1967. We have prepared two versions of the master data tape, both of which are in the standard NODC format. One preserves the data exactly as it was obtained from NODC; the other has had sigma-t, specific volume and dynamic height recomputed using the 1980 equation of state (Millero et al., 1980). We use the second version here.

Figure 5.1. The location of hydrographic sections available in Mazzarelli and Rossby (1983)



## Bracketing the Gulf Stream

In recent years several statistical summaries of eddy potential energy and surface kinetic energies have been published (Dantzer, 1977; Wyrtki et al., 1976). Because these are geographical averages, the meandering Gulf Stream necessarily appears as a broad, rather blurred system. It is well known that this 'eddy' variability reflects primarily path variations of the Stream, not variability of the current itself or state (pressure) changes of individual fluid parcels. In this note we wish to consider the current itself (in natural co-ordinates) between Cape Hatteras and Newfoundland. We do this by selecting hydrographic stations in close proximity to the Stream regardless of where it is located geographically; one might call this 'demeandering' the Stream.

Choosing the hydrographic stations that bracket the Stream is in fact not always simple. Some sections cut across at very oblique angles causing the dynamic height transition to appear very gradual (several hundred kilometres) and wavy due to meandering. Twelve sections were rejected for this reason. In some cases the dynamic height field near the Stream is very complicated, presumably due to the presence of warm and cold core eddies (rings). Nonetheless, these sections are used unless the dynamic height field is too complex to allow a clear determination of the edges of the Stream (4 rejected). Twenty-six sections were incomplete or too confusing to be used, and 55

were south of Cape Hatteras. Of the 157 sections available, about 60 sections east of Cape Hatteras were used in the study. Since many sections had at most two stations in the Stream, it is evident that the Stream is not highly resolved. Thus the Stream's location and especially its width are only approximately known relative to the bracketing stations. Direction of flow is, of course, not known at all.

### A Simple Model of Spatial and Seasonal Change

We consider the spatial and temporal variability of the dynamic height field along each side of the field separately. Specifically we assume that the major sources of variability are the downstream changes and seasonal (steric) forcing. By assuming a simple spatial trend (linear), and that the temporal components are spatially uniform (not entirely obvious), we can remove the former and estimate the temporal signal using a larger data-base than would otherwise be possible. Further, by removing this variability (determined in a least square sense), we can look at the residuals and search for possible secular trends. For comparison, dynamic heights are computed for the depth intervals 0-300 and 0-2000 dbars. The first interval emphasizes seasonal variations, the latter variations due to the main thermocline.

We assume the following model for the dynamic heights,  $d_i$ :

$$\bar{d}_i = a_0 + a_1 x_i + a_2 \cos \omega t_i + a_3 \sin \omega t_i$$

The co-efficient  $a_1$  represents downstream change (per  $10^3$  km),  $a_2$  and  $a_3$  the annual cycle. They are estimated by minimizing the quantity

$$e_1^2 = 1/N \sum_{i=1}^N (d_i - \bar{d}_i)^2$$

The Standard deviation of the data,  $e_0$ , and the residuals after model fit,  $e_1$ , are shown in Table 5.1. The mean difference across the Stream at  $x=0$  ( $73^\circ W$ ) is  $\langle 2.22-1.21 \rangle = 1.01$  dyn.m. and decreases to  $\langle 1.98-1.11 \rangle = 0.87$  dyn.m. at 2000 km ( $50^\circ W$ ). Figs. 5.2a and 5.2b show the variation in the dynamic height anomaly for the Slope Water and Sargasso Sea sides separately. The panels show the seasonal variation with the mean field removed from the original data (Fig. 5.2a) and conversely, the mean field with the seasonal component removed (Fig. 5.2b). The seasonal signal has the same phase in all four cases with a maximum in September (the co-efficient  $a_2$  is always insignificant). The annual variation is always greater on the Sargasso Sea side due to the greater penetration depth of the seasonal thermocline, even though the density variations are larger on the Slope Water side. Note (Table 5.1) the significant reduction of the residuals (from  $e_0$  to  $e_1$ ).

Figure 5.2a. Seasonal variation in dynamic height along the Gulf Stream. The upper and lower panels show the Sargasso Sea and Slope Water sides respectively. The spatially varying mean field has been removed.

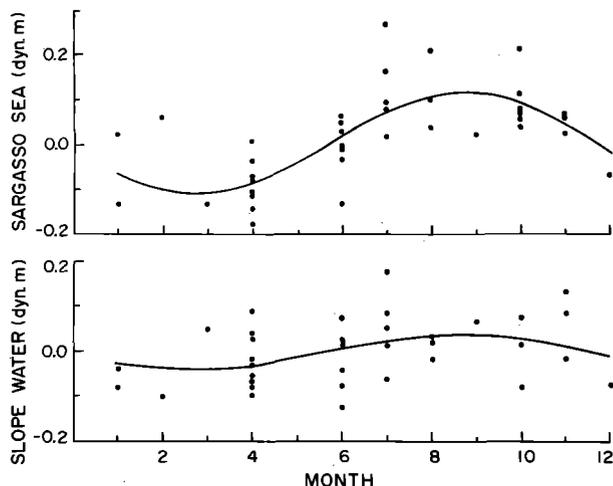


Figure 5.2b. Dynamic height plotted as a function of downstream distance for the Sargasso Sea and Slope Water sides respectively. 0 km corresponds to the 'Pegasus' line ( $73^\circ W$ ) and 700 km to  $65^\circ W$ . The Seasonal cycle has been removed from the data.

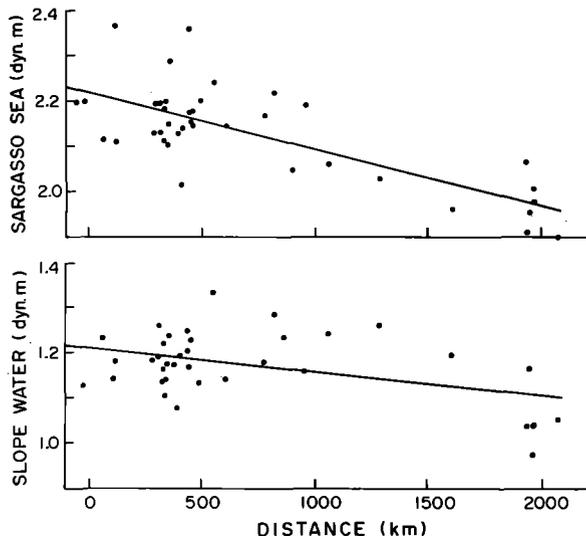


TABLE 5.1

	0 - 300 dbars		0 - 2000 dbars	
	Slope water	Sargasso Sea	Slope water	Sargasso Sea
$a_0$	0.44	0.65	1.21	2.22
$a_1$	-0.06	-0.04	-0.05	-0.12
$a_2$	0.00	0.02	-0.01	-0.01
$a_3$	-0.05	-0.10	-0.04	-0.11
$e_0$	0.07	0.10	0.09	0.15
$e_1$	0.04	0.05	0.07	0.07
N	54	55	36	40

Perhaps the most important point to make here is that the residuals are so small. The variability of the Gulf 'String', as Fuglister once termed the instantaneous Gulf Stream, is clearly much smaller than the large eddy variability levels due to the meandering of the Stream mentioned earlier. They are in fact comparable to those reported by Schroeder and Stommel (1969) for the area around Bermuda. If we assume that the residuals are incoherent, then the r.m.s. variability of the difference is about 0.1 m or ~10% of the mean difference. The seasonal signal is 7% (0.11-0.04) of the total difference; thus the annual variation in surface transport is at most 15% of the mean.

### Comparison with Other Estimates of Dynamic Height

In a recently completed three-year programme of bi-monthly transects across the Gulf Stream near 73° W, sixteen sections of the absolute velocity field (including surface currents) were obtained using the instrument 'Pegasus' (Halkin and Rossby, 1984). From these we can determine, assuming geostrophy, the absolute sea level difference across the Stream. Using 12 complete and independent sections we obtain 1.1±0.09 dyn.m. The difference between this direct estimate and the hydrographic value at x=0 km (the 'Pegasus' line), 1.01 dyn. M., is roughly constant with the observed 'Pegasus' average (150 km wide) downstream speed of 4 cm/s at 2000 m.

Much less is known about the path coherent deep transports further downstream. However, in a recent study Shaw and Rossby (1984) provide information on peak velocities in the Stream as determined from the transit of Sofar floats from one side of the Stream to the other. At 2000 m the peak speeds are at about 30 cm/s, although many times, especially east of 65° W, a deep current could not always be observed even though it was certain that the float had crossed under the Stream. However, in order to construct an estimate of the contribution to the total dynamic height field by the deep currents, let us imagine a deep current having a triangular cross-stream structure with a maximum speed  $v_p$  in the centre and 0 cm/s at the edges. We assume for the moment that this deep transport is always present. The cross stream averaged downstream velocity is  $v_p/2$  and the transport is simply  $Lv_p/2$ , where L is the width. Expressed as a dynamic height we have  $h=Lfv_p/2g$ , where f and g are respectively the Coriolis parameter and gravity. Setting L=150 km, we obtain  $h=0.22$  dyn. m. However, the Sofar float data suggest that the deep current is not always present. How often this is the case we do not know. If it were present half the time and completely absent otherwise, the associated dynamic height difference would be  $0.11 \pm 0.11$  m. This reduces the mean transport and it maximizes the variability. Thus at x=700 km (~65°W) the total dynamic height difference across the path of the Stream would be

$$\langle 2.1-1.2 \rangle \pm 0.1 + \langle 0.1 \rangle \pm 0.1 = \langle 1.0 \rangle \pm 0.14 \text{ dyn.m.}$$

(baroclinic)                      (barotropic)                      (total)

or  $\langle 1.1 \rangle \pm 0.2$ , should it turn out that the baroclinic and barotropic fluctuations are in phase. The  $\langle \rangle$  denotes the mean difference.

These numbers disagree with Seasat altimetry estimates of sea level difference across the Gulf Stream. Cheney and Marsh (1981) quote surface transport variations of nearly 30% on time scales of a few days, and much larger fluctuations over the entire three-month period of the Seasat mission, specifically

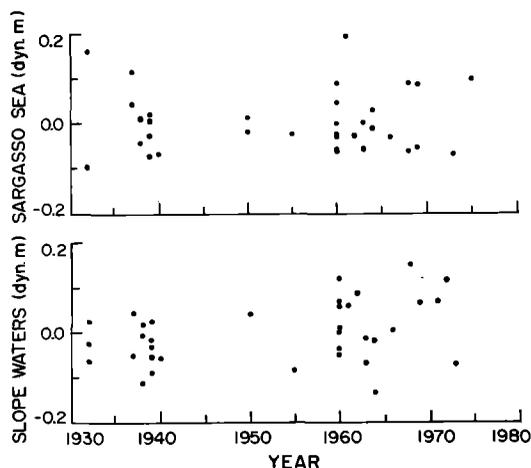
$$\langle 1.40 \rangle \pm 0.35 \text{ m.}$$

We do not know the reason for the discrepancy in both the mean difference as well as the variability, both of which are much larger. One possibility might be that, contrary to our assumption, the deep current is broader than the baroclinic current. A difficulty with this explanation is that the Cheney and Marsh (1981) data shown from the three-week repeating orbits (8 passes) transect the Stream at 71°W, which is only 200 km from the 'Pegasus' study, where, as we discussed above, there is good agreement between the absolute velocity measurements and the hydrography. Yet the altimetric sea level difference is significantly larger,  $\langle 1.39 \rangle \pm 0.11$  m. The considerable reduction in standard deviation is curious; perhaps the 8 passes are not fully independent observations of the Stream. It is beyond the scope of this note to speculate on the reasons for disagreement, but the consistency between the hydrography and the absolute velocity 'Pegasus' data suggests that there may be unresolved discrepancies in the altimetry information. Perhaps these questions can be pursued during the upcoming 'Geosat' mission.

### Evidence for Secular Change

In Fig. 5.3 we show the residuals of dynamic height plotted as a function of time. It is quite striking how little change there has been between the pre- and post-World War II periods. In Table 5.2 we show the mean dynamic height, standard deviation and standard errors for the 1930s and the 1960s for the two sides separately. There is, in these data, no evidence for change in surface transport during the 30-40 years.

Figure 5.3. Residuals of dynamic height plotted against time after the spatial and temporal components have been removed from the data. The Sargasso Sea and Slope Water sides are shown separately in the upper and lower panels.



We are presently conducting a detailed study of these and other sections for evidence of seasonal and secular change in volume transport by the Gulf Stream.

TABLE 5.2

	Slope water		Sargasso Sea	
	1930s	1960s	1930s	1960s
mean	-0.026	0.020	0.000	-0.001
std dev.	0.045	0.074	0.072	0.076
std error	0.012	0.019	0.019	0.017
N	15	16	15	20

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## 6. A 16 year Series of Observations of Sea Surface Temperature and Wind Stress Field in the Tropical Atlantic

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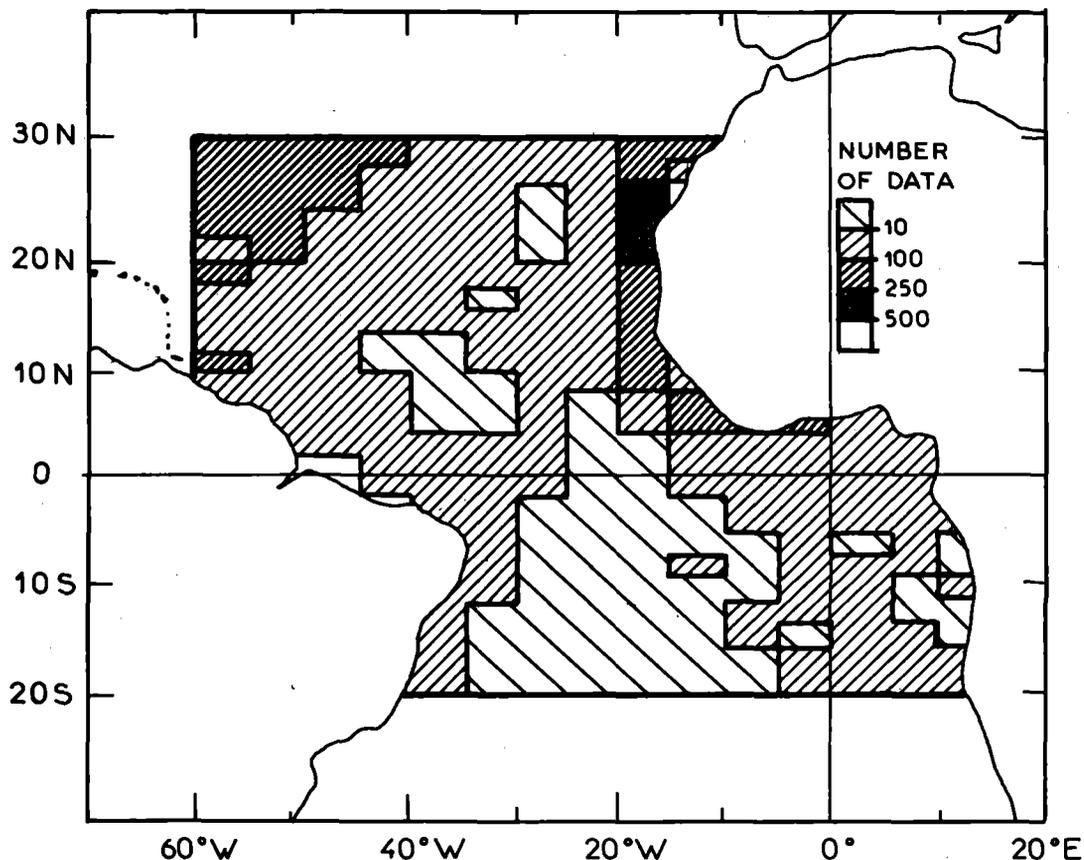
Prior to the start of the FOCAL-SEQUAL experiment, the French group for historical data analysis obtained from the National Climatic Center, Asheville, N.C., all available ship observations in the tropical Atlantic ocean through December 1979. The low number of observations in the Southern Hemisphere led us to choose the limited area 20° S to 30° N, from 60°W to the African Continent (Fig. 6.1). As a result of a greater international emphasis on securing ship reports, the number of observations since World War II increased suddenly after 1963. Hence, the present study covers the period 1964-1979 and is based on nearly two million wind observations and a slightly lower number of Sea Surface Temperature (SST) observations: The total number of observations for each individual year is of the same order with maximum in 1970 and minimum in 1971 (Fig. 6.2). Due in part to the relatively small size of the Tropical Atlantic Ocean, the data density is greater and better distributed than in the tropical Pacific Ocean, especially within the equatorial belt.

The initial processing step was to compute average monthly SST and wind stress for each box of 2° latitude by 5° longitude. The size of each quadrangle is half that used by Wyrтки and Meyers (1975) and Goldenberg and O'Brien (1981). In this note, the term "wind stress" represents the two components :

$$\tau^x = \sum_{i=1}^N w_i^x \cdot |\vec{w}_i| \quad \text{and} \quad \tau^y = \sum_{i=1}^N w_i^y \cdot |\vec{w}_i|$$

where  $|\vec{w}_i|$  is the wind velocity of the  $i^{\text{th}}$  observation of a total of  $N$  in the considered box, and  $w_i^x, w_i^y$  the zonal and meridional wind components, respectively. To obtain a dimensionally correct value of the wind stress,  $\tau^x$  and  $\tau^y$  would be multiplied by an air density and drag co-efficient which may or may not be constant, according to various empirical formulas. When computing the monthly averages, the data within

Figure 6.1 Study area with monthly mean numbers of data by 2° x 5° boxes.



each grid box were subjected to a series of tests. Each temperature measurement outside the range  $10^{\circ}\text{C}$  to  $31^{\circ}\text{C}$  and each wind measurement greater than  $25 \text{ m.s}^{-1}$ ; such as that representing a tropical cyclone, was rejected. The data within any  $2^{\circ} \times 5^{\circ}$  box were completely ignored if there were at most two SST observations or only one wind observation. For less than 8 observations per grid box (approximately one fourth of all possible boxes) particularly careful proceedings were used on both parameters. The mean value of SST was tested against the climatic mean using a Student's test of homogeneity. An approach was then used to compare the homogeneity of this box to the homogeneities of all surrounding boxes. Ten percent of the grid boxes in this category failed the test. For the wind observations, this automatic test was replaced by a subjective analysis requiring that the direction and magnitude at each point in question be visually inspected on a graphic terminal. Twenty percent of the grid points containing less than 8 wind observations, were analysed. When the number of SST or wind observations was greater than or equal to 8, the range of the data within each grid box was tested against a normal distribution. Depending on the scatter of the observations, 2% - 10% of the data in such a grid square were rejected. The last in this series of tests was the inspection of each monthly SST and wind stress map for any remaining spurious anomalies. Two percent of all the boxes required a subjective analysis that took into account data from surrounding grid points in time and space. Fig. 6.3 gives an example of such a corrected map.

Finally, an objective analysis method based on Cresman (1959) was used to obtain a database of

monthly averaged SST and wind stress components on a  $2^{\circ} \times 2^{\circ}$  grid. The convergence of this method can give spurious extrapolations when there are large areas of missing data (mostly in the south central part of the study area). This was prevented by "seeding" such regions with subjectively analysed data. A total of 2% of all possible grid points were entered in this manner. The choices of influence radii and iteration count for the objective analysis scheme were based on visual comparisons with contour fields of the  $2^{\circ} \times 5^{\circ}$  data, statistical analysis and discussions with experienced meteorologists. The radii of influence, in descending order, were : 1400 km, 1000 km and 3 times on 600 km for SST, and 1600 km, 1200 km and 4 times on 800 km for the wind stress components. Figs. 6.4 and 6.5 give examples of the final monthly maps.

Figure 6.2. Total yearly numbers of data from 1964 to 1979.

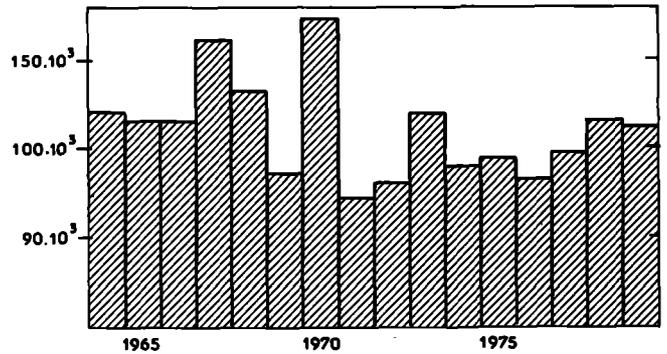


Figure 6.3. An example of a  $2^{\circ} \times 5^{\circ}$  corrected wind stress map.

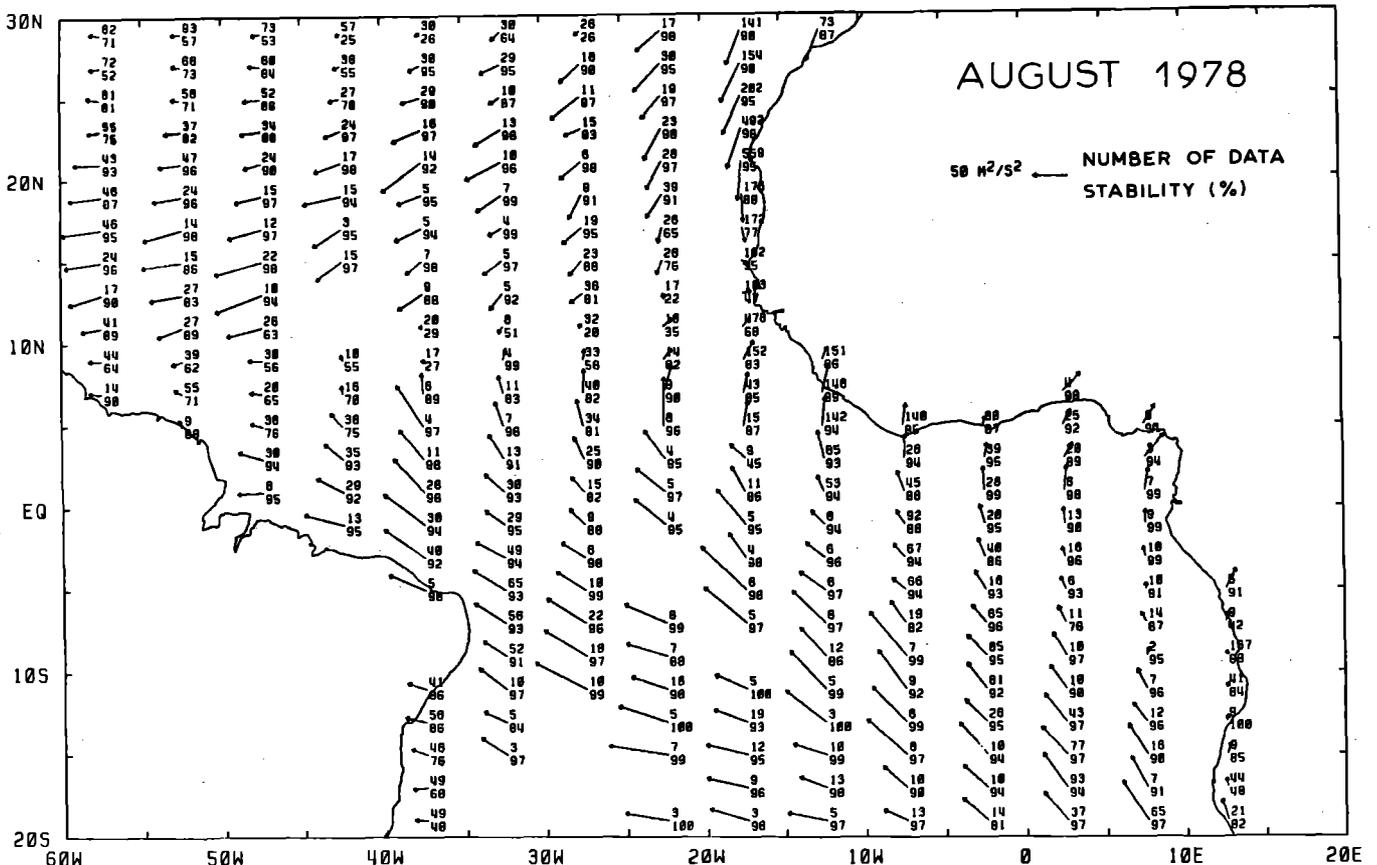


Figure 6.4. An example of a final  $2^\circ \times 2^\circ$  sea surface temperature map (in  $^\circ\text{C}$ ).

AUGUST 1978

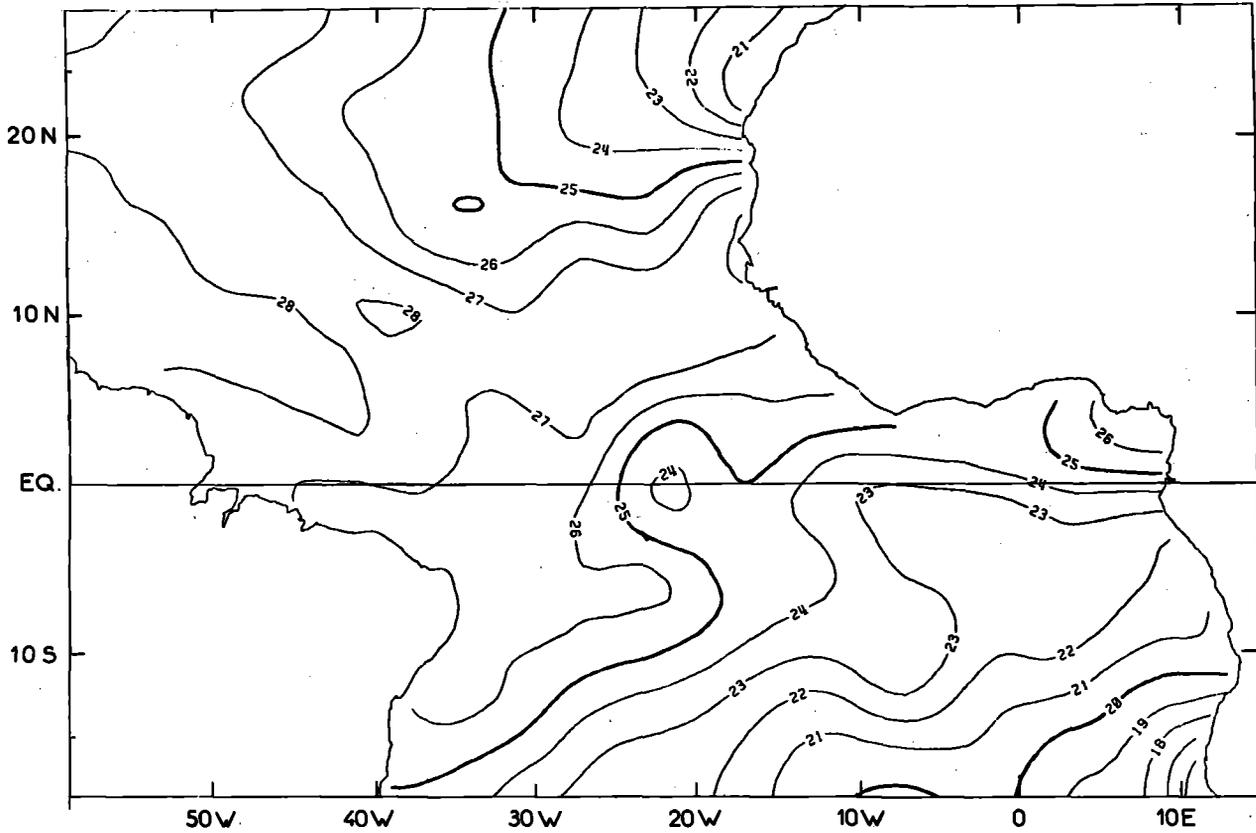
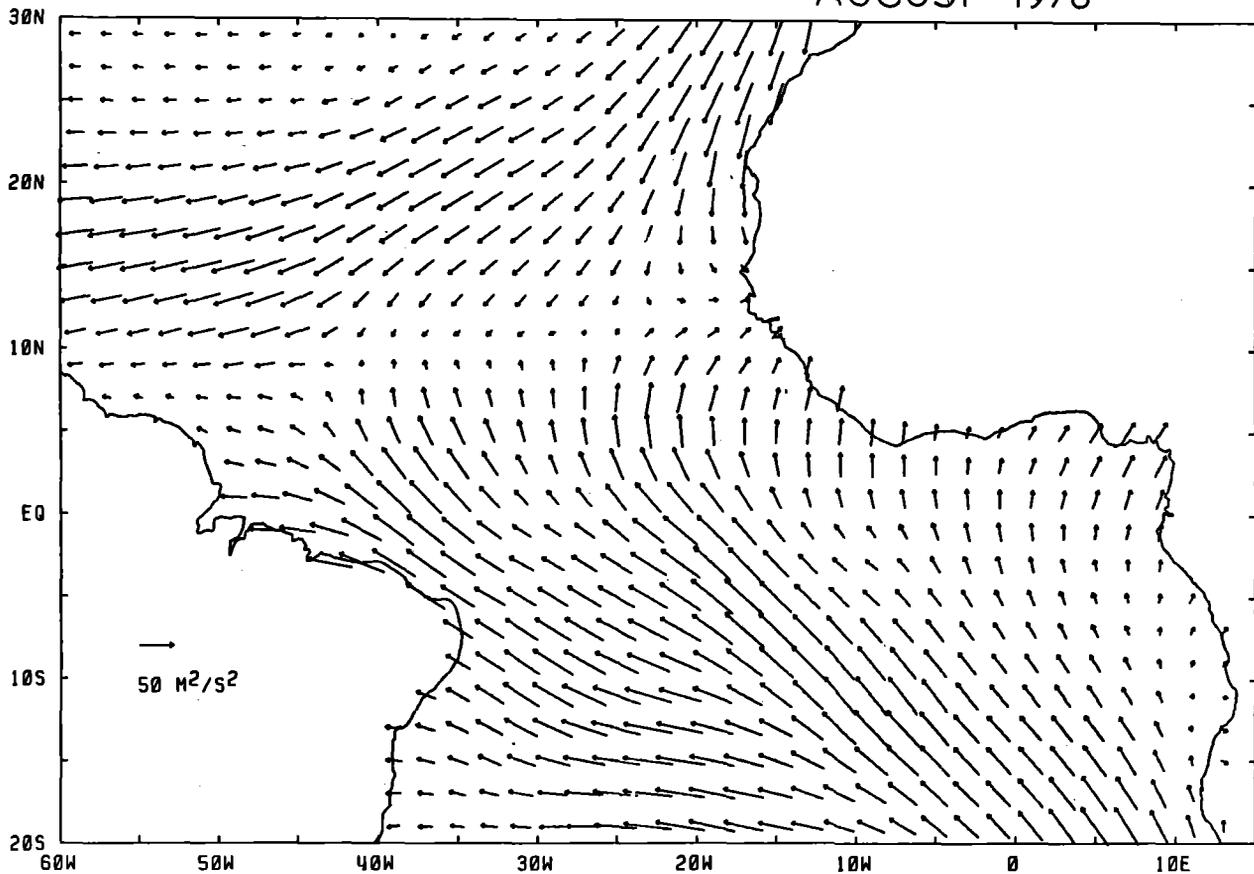


Figure 6.5. An example of a final  $2^\circ \times 2^\circ$  wind stress map.

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All the corresponding figures of the 16-year  $2^{\circ}$  x  $2^{\circ}$  gridded SST and wind stress data will be published in an atlas by the end of 1984. These data also provide an opportunity to jointly analyse the seasonal and inter-annual variability throughout the basin. The presence of multiple years of wind data on a regular grid also permits the inter-annual wind-driven response of the tropical Atlantic to be modelled. Preliminary results of such studies are given in Picaut *et al.*, according to which the inter-annual variability in the tropical Atlantic may not be as small as once thought. Many other studies will be attempted, such as empirical orthogonal function analyses, possible correlations with the Sahel and N.E. Brazil droughts and with the Southern Oscillation (a similar 16-year barometric pressure field series will soon be established).

## Acknowledgements

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# 7. Comparison of Sea Level Variability on the Caribbean and the Pacific Coasts of the Panama Canal

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## Introduction

Within six years of the acquisition of the Panama Canal Zone by the United States in 1903, the coastal towns of Cristobal and Balboa (Fig. 7.1) became sites for permanent tide gauge stations operated by the U.S. Coast and Geodetic Survey. The observations from these sites form an unique data set that enables us to compare seasonal and interannual sea level variability in separate but adjoining oceanic basins for which the influence of local barometric pressure and prevailing winds are nearly identical. Marked differences in the sea level records should be indicative of differences in the basin-wide responses.

## General Features

Continuous records of monthly mean sea level for Cristobal and Balboa for the period 1909 to 1969 have been obtained from the Permanent Service for Mean Sea Level (IOS, England) courtesy of Dr. D.T. Pugh; corresponding atmospheric pressures are available for Cristobal only and span the period 1922 to 1961 (Fig. 7.2 a-c). The data appear to be of generally good quality except for possible erroneous negative values in the Balboa sea levels for January 1958 and July 1967 (marked by an

asterisk in Fig. 7a). Comparison of the Balboa sea levels with those of Puerto Armuelles and Naos Island (Fig. 7.1) suggests that the July 1967 value is particularly suspect. Therefore, for those instances where the July 1967 value has a significant effect on a derived quantity, the quantity has been determined using both the original record and a modified record in which the July value is replaced by the mean value between June and August.

Figure 7.1. Map of region

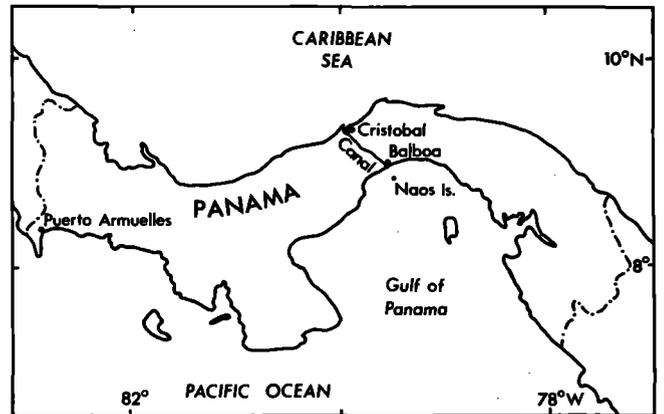


Figure 7.2. Monthly-mean sea level height at Balboa and Cristobal and sea level pressure at Cristobal. Horizontal lines in a and b denote mean values for the detrended time series. Record averaged means are given in Table 7.1.

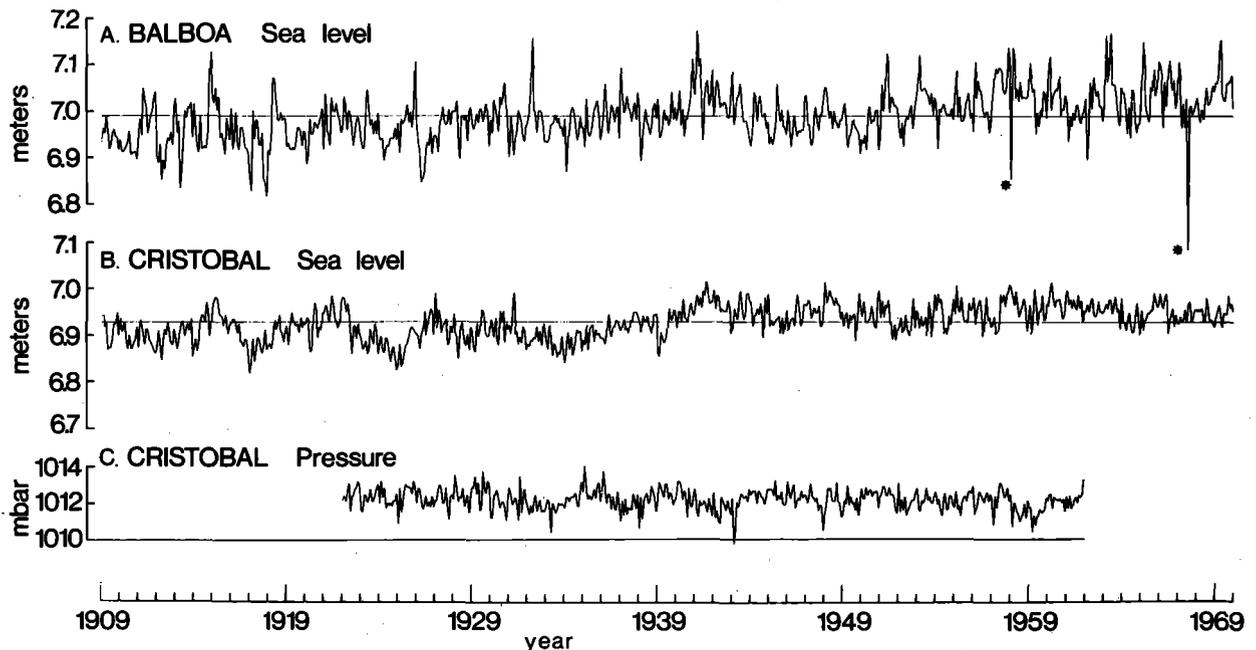


Fig. 7.2 reveals obvious differences in the amplitude of the three signals. For example, on the Pacific Ocean side of the Isthmus of Panama, the root mean square (rms) amplitude of the detrended sea level record is 11.3 cm compared to 4.3 cm on the Caribbean side (Table 7.1). Use of the classical inverse barometer response of 1.01 cm/mb yields an equivalent rms amplitude of only 0.08 cm for the shorter pressure record (corresponding values for Balboa and Cristobal over the same period are 10.9 cm and 4.5 cm, respectively). Because the spatial scales of atmospheric disturbances are typically large compared to the 60 km width of the Isthmus, we expect atmospheric pressure variations at Balboa to be nearly identical to those at Cristobal. Pressure fluctuations of such low magnitude are typical of equatorial regions and suggest that, contrary to mid-latitudes, direct barometric forcing has a minor influence on coastal water levels.

The mean sea level at Balboa for the period of observation was slightly higher than at Cristobal (assuming that the two sites have been correctly geodetically levelled) and had a somewhat greater positive trend (Table 7.1). Over the 61 years of data, the mean sea level at Balboa increased by 9.6 cm and that at the Cristobal by 6.8 cm. This indicates a greater rise in Pacific Ocean water levels and/or a greater subsidence of the Pacific coast relative to the Caribbean coast. In contrast, the negative trend in sea level pressure is not considered significant as it amounts to less than -0.4 mb in 40 years.

Following Thomson and Tabata (1982), we next look for effective values for the barometric response parameter,  $\alpha$ , that minimize (in the least squares sense) the right hand side of (1). The results ( $\alpha = 1.47$  cm/mb for Cristobal and 8.59 cm/mb for Balboa) lead to respective reductions of 0.4% and 19.1% in the rms amplitudes of sea level records relative to the case for the classical inverse barometer effect. We interpret this to mean that, on the Pacific side, atmospheric pressure fluctuations are moderately well correlated with other mechanisms (e.g. winds, coastal currents and run-off) that are responsible for changes in coastal sea levels. On the Caribbean side, such correlations are either weak or the various forcing mechanisms tend to cancel one another.

### Spectra and Coherences

Spectra for the Cristobal and Balboa records are presented in Fig. 7.3. The sea level records are dominated by annual and semi-annual components and there are moderately large spectral levels at periods longer than about 2 years. In the pressure record, there also is evidence of a broad energetic band centred near 0.0145 cpmo, corresponding to a period of around 5.7 years. This band has been noted previously in mid-latitude sea levels, temperatures and even fish catch records (e.g. Thomson and Tabata, 1982; Mysak et al., 1982). However, the best evidence for a 5-6 year atmosphere-ocean oscillation emerges from the

**Table 7.1 Features of the Panama sea level and atmospheric pressure records. Sea level amplitudes are in cm, pressure amplitudes in mb. Bracketed values for Balboa are for record with interpolated July 1967 value.**

Location	Duration months	Mean (cm, mb)	Stand. dev. (cm, mb)	Trend (cm/mo, mb/mo)	Effective (cm/mb)
Balboa sea level	732	703.3 (703.4)	11.3 (11.2)	$1.32 \times 10^{-2}$ ( $1.35 \times 10^{-2}$ )	8.59
Cristobal sea level	732	695.8	4.3	$0.92 \times 10^{-2}$	1.47
Cristobal pressure	480	1010.8	0.8	$-0.78 \times 10^{-3}$	-

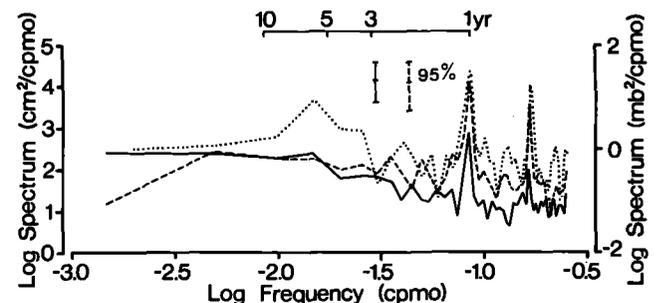
### Adjusted Sea Levels

The comparatively small variance in atmospheric pressure at Cristobal implies that adjusted (pressure-compensated) sea levels,  $H_a$ , should differ little from the uncorrected values,  $H$ . In fact, adjustment for the classical inverse barometer effect ( $\alpha_0 = 1.01$  cm/mb) via the relationship

$$H_a = H + \alpha \cdot P \quad (1)$$

reduces the rms amplitude of the Balboa and Cristobal records by less than 5% ( $P$  is the atmospheric pressure fluctuation about the mean). Non-adjusted sea levels are therefore almost indistinguishable from the actual values and the longer records can be used.

**Figure 7.3. Spectra of Balboa sea level (—), Cristobal sea level (---) and Cristobal sea level pressure (....). The solid 95% confidence interval applies to the sea level records, the dashed interval to the shorter pressure record. cpmo=cycles per month.**

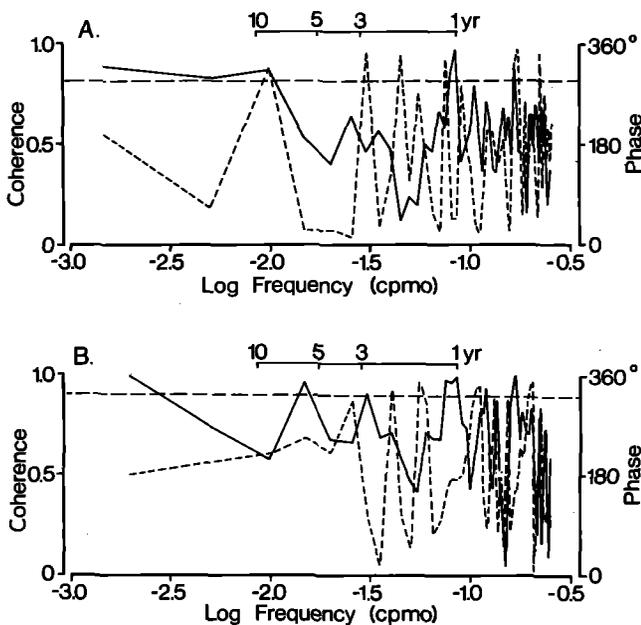


comprehensive study of Quinn et al. (1978). If we use the data in their Table 3 (dating back to 1971) and include the strong event of 1982-1983, we find a time of  $5.5 \pm 3.7$  years between the onsets of moderate-to-strong El Niño-Southern Oscillation events.

The coherence between the two detrended sea level records is presented in Fig. 7.4a. The amplitude exceeds the 99% confidence level (0.91) at the annual and semi-annual period and the 95% level (0.82) at periods longer than about 8 years. At the annual period, sea level fluctuations at Balboa lead those at Cristobal by  $46^\circ$  (1.5 months) while at the semi-annual period Balboa lags Cristobal by  $34^\circ$  (0.6 months). No consistent phase difference is found at the lowest frequencies.

The coherence between Balboa sea level and Cristobal pressure are plotted in Fig. 7.4b. As with the sea level records, coherence amplitudes exceeds the 95% confidence level (0.94) at the annual and semi-annual periods. At low frequencies, sea levels and pressures are coherent at the 95% level only near 0.0146 cpmo, coincident with the 5.7 year peak in the sea level pressure record (Fig. 7.3). The sea levels at Cristobal lead atmospheric pressure by  $120-130^\circ$  (4-4.5 mo) at the same annual period and by roughly  $180^\circ$  (3 mo) at the semi-annual period; Balboa lead pressure by  $170-180^\circ$  at the annual period and by  $150^\circ$  at the semi-annual period. In contrast, sea levels lag pressure at the coherent 5.7 year period. The lags are roughly  $160^\circ$  (30 mo) and  $110^\circ$  (21 mo) for Cristobal and Balboa, respectively.

**Figure 7.4.** Coherence amplitude (—) and phase (---). (a) Balboa sea level versus Cristobal sea level; (b) Balboa sea level versus Cristobal pressure. Phase gives lead of Balboa over Cristobal records. Horizontal line is 95% confidence level.

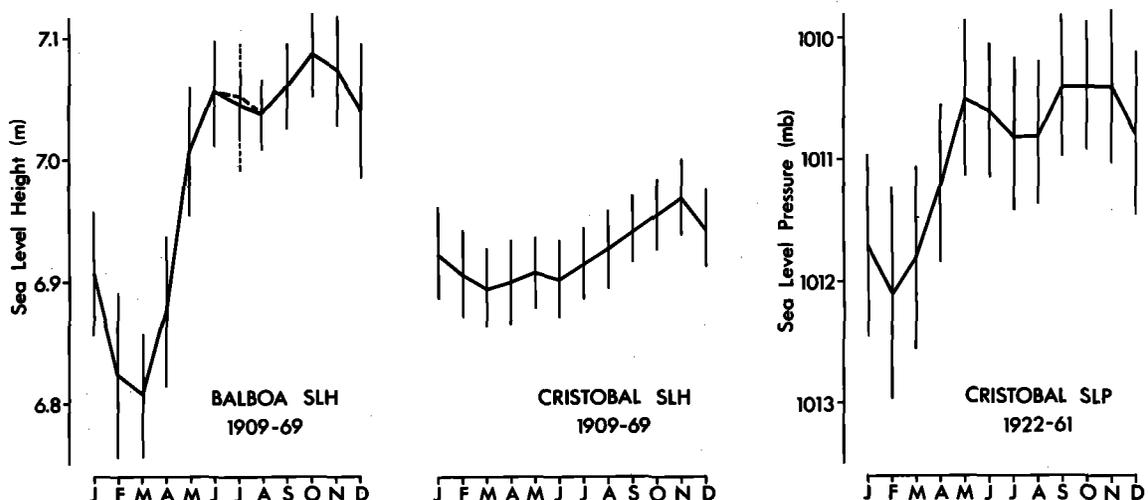


### Interannual Variability

We now wish to compare the pressure and sea level variability with the occurrences of known El Niño-Southern Oscillation (ENSO) events. To do this we first detrended the records and calculated the mean-monthly (record-averaged) values along with the corresponding monthly standard deviations (Fig. 7.5). In this case, the low sea level value of July 1967 at Balboa has a significant effect on the mean and standard deviation so the analysis is performed using both the original and modified Balboa sea level records. The mean-monthly values were then subtracted from the detrended time series to produce monthly anomaly records; the sea level versions of these time series are plotted in Fig. 7.6. Lastly, we generated annual anomaly records by averaging the sea levels and pressures over each year, then subtracting the long-term (record-averaged) values. For plotting purposes, the latter have been normalized by dividing each anomaly record by its standard deviation (Fig. 7.7). The arrows in Figs. 7.6 and 7.7 denote the onset times of weak (w), moderate (m) and strong (s) ENSO events according to the classification of Quinn et al. (1978).

The results in Fig. 7.5 emphasize the dominant annual cycle in the mean sea level height at Balboa and the comparatively weak annual cycle at Cristobal. Mean sea level pressure fluctuations in

**Figure 7.5.** Mean-monthly sea level heights (SLH) and sea level pressure (SLP). Vertical bars denote standard deviations about the mean. Dashed lines in Balboa plot are based on modified record using an interpolated value for July 1967. Pressure axis is inverted.

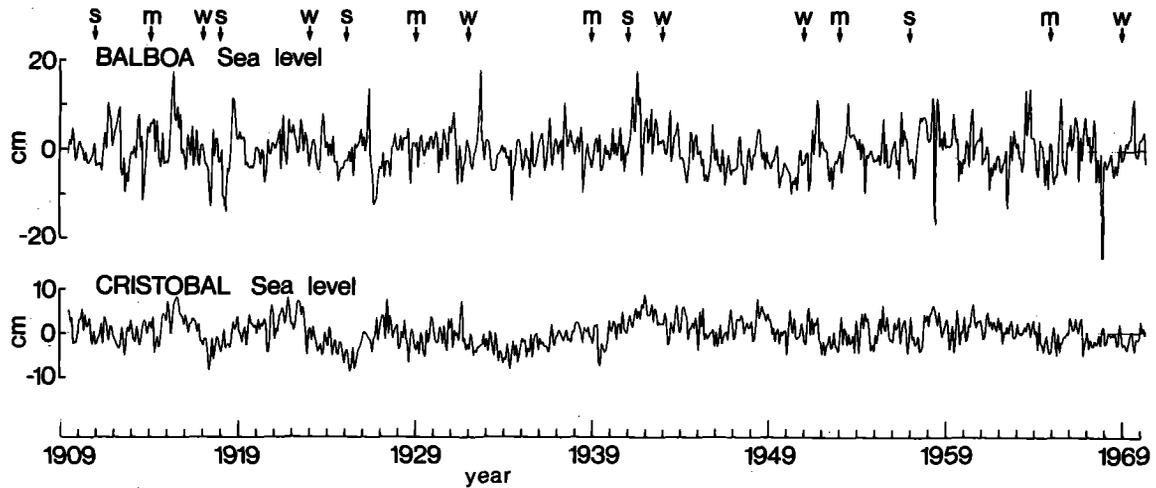


the area resemble an inverted version of the Balboa sea level variations although the order 1 mb pressure amplitude is clearly too small to account directly for the 10-15 cm amplitude in the annual sea level variations. Standard deviations also vary throughout the year with highest values in Winter (December-March) and lowest values in Summer (August-October). The interannual variability that produces the monthly differences in the standard deviations is especially pronounced in the Balboa sea level record (Fig. 7.2a). Specifically, the factor of two reduction in the standard deviation between June and July for the modified Balboa sea level record may be associated with an abrupt change in local wind, current or runoff patterns. Such an abrupt change does not occur on the Caribbean side. Alternately, the June-July "discontinuity" may reflect differences in basin-wide responses, with July possibly marking the time of rapid collapse of El Niño events in the eastern equatorial Pacific.

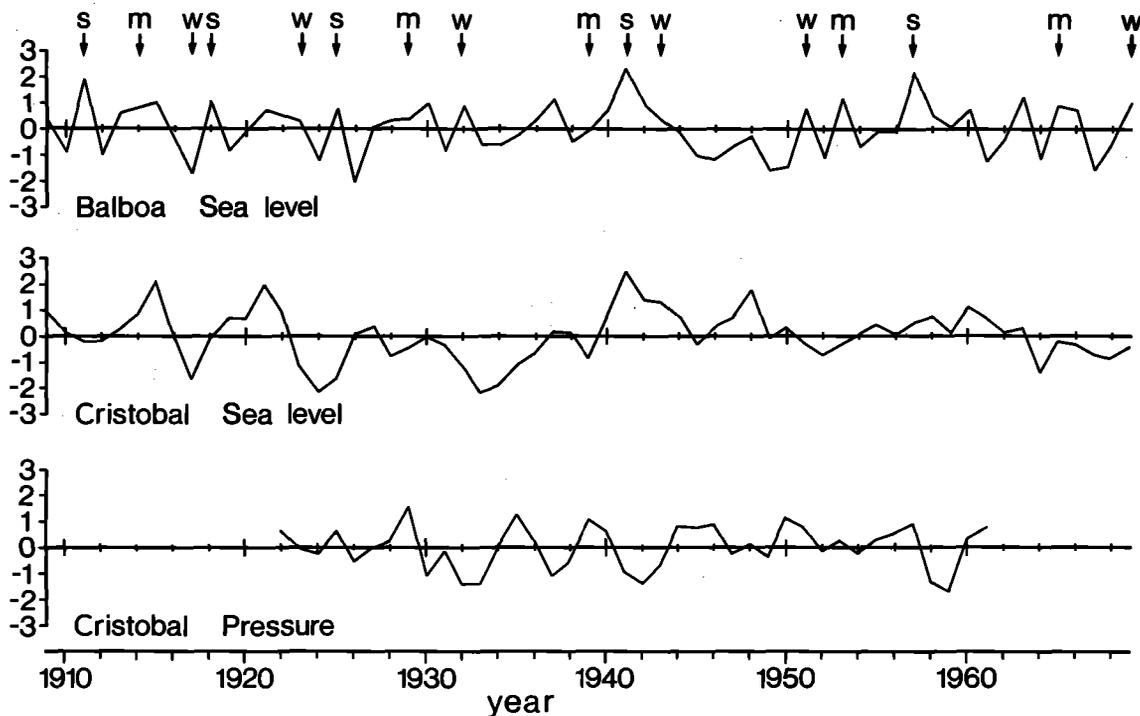
The anomaly time series in Figs. 7.6 and 7.7 show that all major (strong) ENSO events, with the exception of the 1925-26 event, produced large and protracted rises in sea level at Balboa. The annual anomalies in each case exceeded 1.5 standard deviations. (For a normally distributed variable this can occur by chance with a probability of 0.067.) Moderate ENSO events also led to sea level rises at Balboa although the corresponding anomalies are typically less than one standard deviation. There is no evidence that weak events influenced the sea levels.

Of the five strong events between 1909 and 1969, only the 1940-41 event was associated with a significant rise in sea level at Cristobal. The sea level peak in 1915 may have been linked to the moderate ENSO event of that year while the distinct peaks of 1921 and 1948 had no El Niño counterpart according to the findings of Quinn *et al.*

**Figure 7.6.** Time series of monthly sea level anomalies. Letters refer to onset years of weak (w), moderate (m) and strong (s) ENSO events according to Quinn *et al.* (1978). The Balboa anomaly record has a standard deviation of  $4.7 \pm 1.2$  cm, the Cristobal record a deviation of  $3.2 \pm 0.4$  cm.



**Figure 7.7.** Normalized, yearly-averaged anomaly records. The vertical axis gives the annual anomaly in units of one standard deviation. Arrows as in Fig. 7.6.



## Summary

The results of this report can be summarized as follows:

- (1) The rms amplitude of monthly-mean sea level fluctuations along the central Pacific coast of Panama is approximately three times greater than along the adjacent Caribbean coast.
- (2) Between 1909 and 1969, sea level rose 9.6 cm at Balboa and 6.8 cm at Cristobal indicating differences in basin-wide sea level changes and/or a greater tectonic subsidence on the Pacific side of the Isthmus of Panama.
- (3) Sea level pressure fluctuations in the region are small and directly account for only minor variations in sea level. In contrast, the calculated effective barometric response for Balboa ( $\alpha = 8.59$  cm/mb) reduces the standard deviation of the sea level record by over 25%. This indicates that, on the Pacific side, the pressure variations are well correlated with mechanisms such as wind, runoff and current that modify the coastal sea levels.
- (4) Sea level and sea level pressure fluctuations in the region are predominantly at annual and semi-annual periods. The pressure record has a secondary peak centred at 5.7 years comparable to the period of  $5.5 \pm 3.7$  years between the onsets of moderate-to-strong ENSO events.
- (5) At low frequencies, sea levels and atmospheric pressure are coherent above the 95% confidence level only for the frequency band centred at period 5.7 years. Within this band, sea levels lag pressure by roughly 20-30 months.
- (6) The standard deviation of the monthly sea level records are greatest in winter and least in summer. At Balboa, there is a factor of two reduction in the deviation between June and July which may mark the time that El Niño events collapse in the equatorial Pacific Ocean.
- (7) Strong-to-moderate ENSO events clearly effect higher sea levels along the Pacific coast of Panama. However, only the strong 1940-1941 event, and possibly the moderate 1915 event, produced a significant sea level rise on the Caribbean side. Major sea level rises at Cristobal in 1921 and 1948 were not linked to ENSO events.

An extension of the present analysis to include more recent sea level and pressure data is in progress.

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## 8. Hydrostation 'S' off Bermuda in 1983

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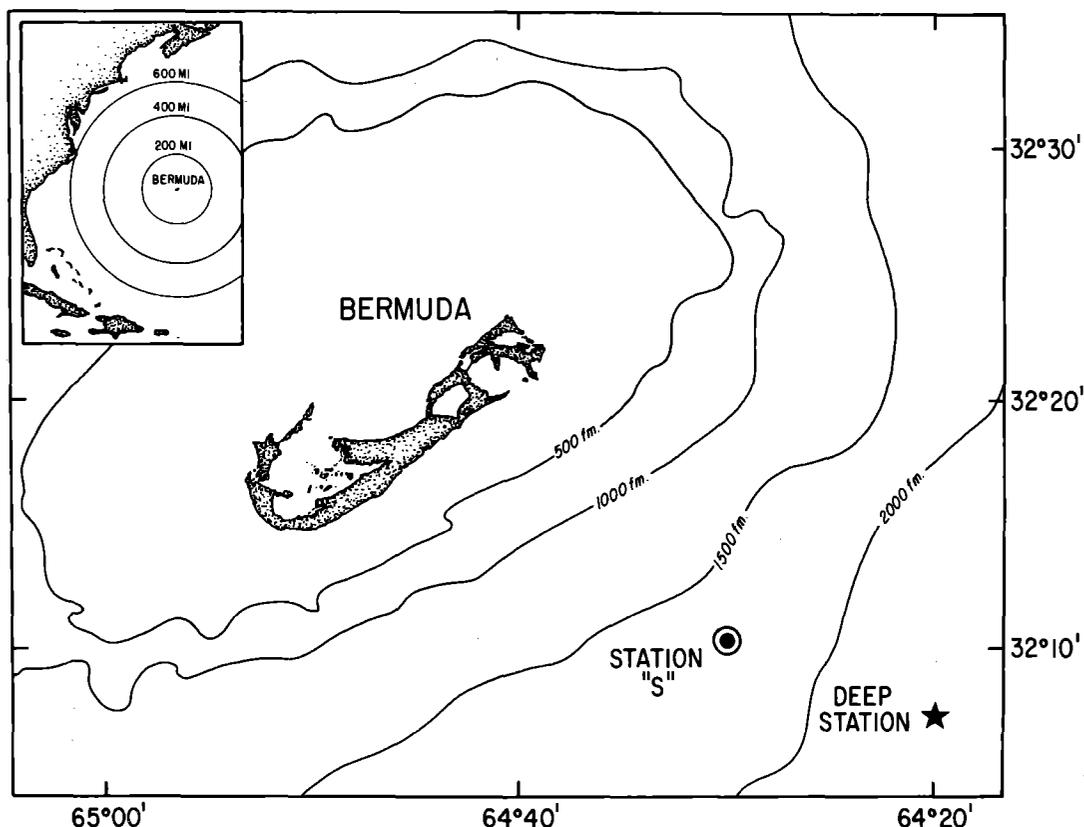
The longest series of deep-sea oceanographic stations in the world has been maintained since 1954 at 32°10'N, 64°30'W, 13 miles (20 km) southeast of Bermuda (Fig. 8.1) Wright and Knap, 1983). Since the demise of the weather ships it has been the only regularly reporting station in the western North Atlantic Ocean. There have been 532 stations in 29 years, roughly one every three weeks, with slight bias toward the calmer summer months.

Each station consists of two casts with water bottles equipped with reversing thermometers. Temperatures and samples are obtained at 26 depths down to 2600 m in water 3000 m deep. Starting in 1983, the samples were taken in Niskin bottles, usually of 5-litre capacity; Nansen bottles had been used previously. Temperature, salinity and dissolved oxygen have been reported routinely; measurements of nutrients, chlorophyll, primary production and other variables have been made from time to time. The entire series is on file with the U.S. National Oceanographic Data Center; data reports through 1973 are available from the Bermuda Biological Station (BBS).

This report covers stations 507 to 532, from 27 January to 28 December 1983. These were the first stations to be made from R/V Weatherbird, which replaced Panulirus II in 1983. Weatherbird made 23 regular stations at Station 'S', two in every month but January. In addition, there were three deep stations at a new offshore location, 32°07'N, 64°20'W. The deep stations consists of three casts to 4000 m in 4200 m water depth. They were instituted to extend the time series into deeper water and to provide some idea of how representative station 'S' may be of locations further offshore.

Use of the larger Niskin bottles has made it possible to provide additional samples for other investigators. In 1983 these included Dr. W. Jenkins of Woods Hole Oceanographic Institution (WHOI) for measurement of tritium; Dr. C. Measures (MIT) for beryllium, and Dr. C. Keeling (Scripps) for carbon dioxide in surface waters. A monthly collection programme for *Sargassum* spp. for Dr. H. Pestana (Colby College) started in 1983. The research group at BBS has 'piggy-backed' monthly measurements of primary productivity,

Figure 8.1. Location of hydrostations off Bermuda



nutrients and trace metals in the euphotic zone. Measurements of organochlorines have been made in surface waters by Dr. Knap (BBS). Dr. D. Biggs (Texas A&M) investigated the distribution of zooplankton. In August, Dr. P.J. LeB. Williams (Bigelow Laboratory) carried out an intercalibration programme on primary productivity measurements.

Samples of particulate matter were taken on a monthly basis for Dr. Deuser's (WHOI) Ocean Flux Programme. Dr. P. Geschwend (MIT) made measurements on polynuclear aromatic hydrocarbons, Dr. E. Boyle (MIT) made measurements for lead, and Mr. J. Bird (Florida State University) collected water for the analysis of tin.

The 1983 temperature and salinity values are plotted against time in Figs. 8.2 and 8.3; note the depth scale change between 1200 and 1400 m. Two features of the temperature structure are especially noteworthy. First, the upper layers and thermocline region are somewhat cooler in 1983 than in both 1982 and the long-term mean. For example, the 18°C isotherm in 1983 averaged 40m shallower than in 1982, 28m shallower than the long-term mean (Table 8.1); the 20°C isotherm dipped below 100m only in August; and the 15° and 10° averages were also shallower than normal. In contrast, 1982 was marginally warmer than usual (Wright and Knap, 1983). Second, although the isotherms were relatively constant in depth from January to August, disturbances of the order of a month or more characterized the rest of the year, with vertical fluctuations of more than 100m in the mid and upper thermocline. The disturbances did not extend to the sea surface nor were they clearly present below about 1500m. It was conjectured that

they were related to the passage of one or more cold-core Gulf Stream rings which would have lost any distinguishing surface signature before reaching Bermuda. Sea surface temperatures followed the usual pattern, dropping below 20°C from February to April and exceeding 25°C from June to late October; however, the maximum of 28.39° measured in August was a full degree warmer than the 1982 maximum.

The 1983 temperature-salinity plot (not shown) has the usual tight correlation below the depth of seasonal influence. The mid-depth isohalines, therefore, show the same patterns as the isotherms: relatively flat through August, fluctuating thereafter (Fig. 8.3). There was occasional evidence of anomalously fresh water in the upper 200m: some isolated surface values fresher than 36.5‰ in early Winter, and the near disappearance of waters more saline than 36.5‰ in late October.

Table 8.1. Mean isotherm depths at Station 'S'

Isotherm	Mean isotherm depths (metres)		
	1983	1982	18-year mean
18°C	255	295	283
15°C	586	609	601
10°C	823	833	826
5°C	1289	1253	1260

Figure 8.2. Temperature (°C) from Stations 507 to 532 (January-December 1983) plotted against time.

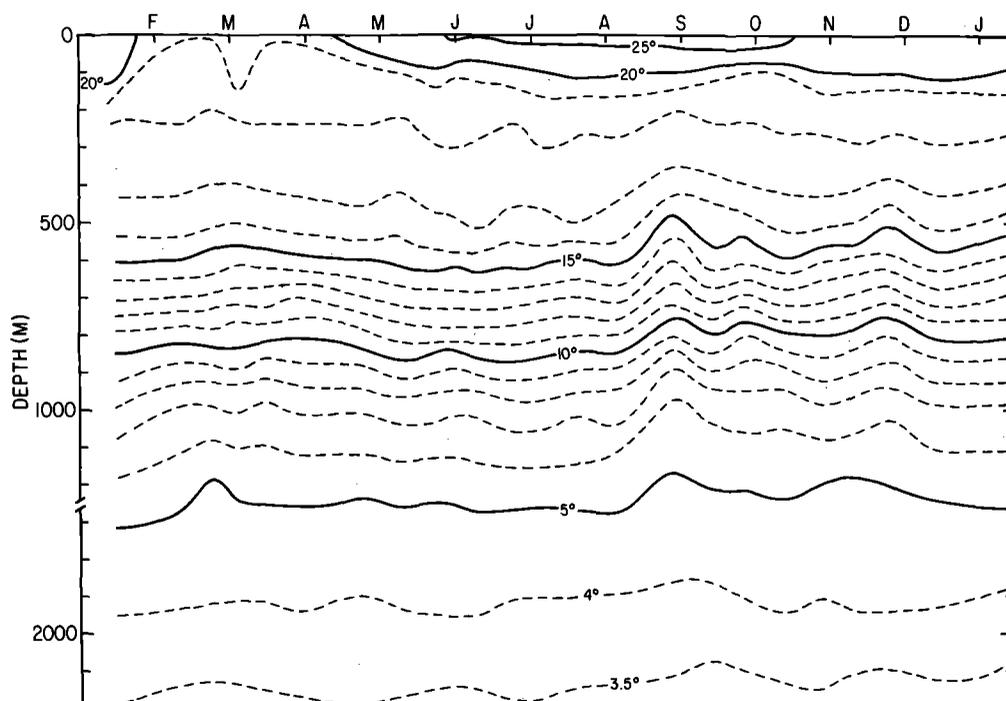
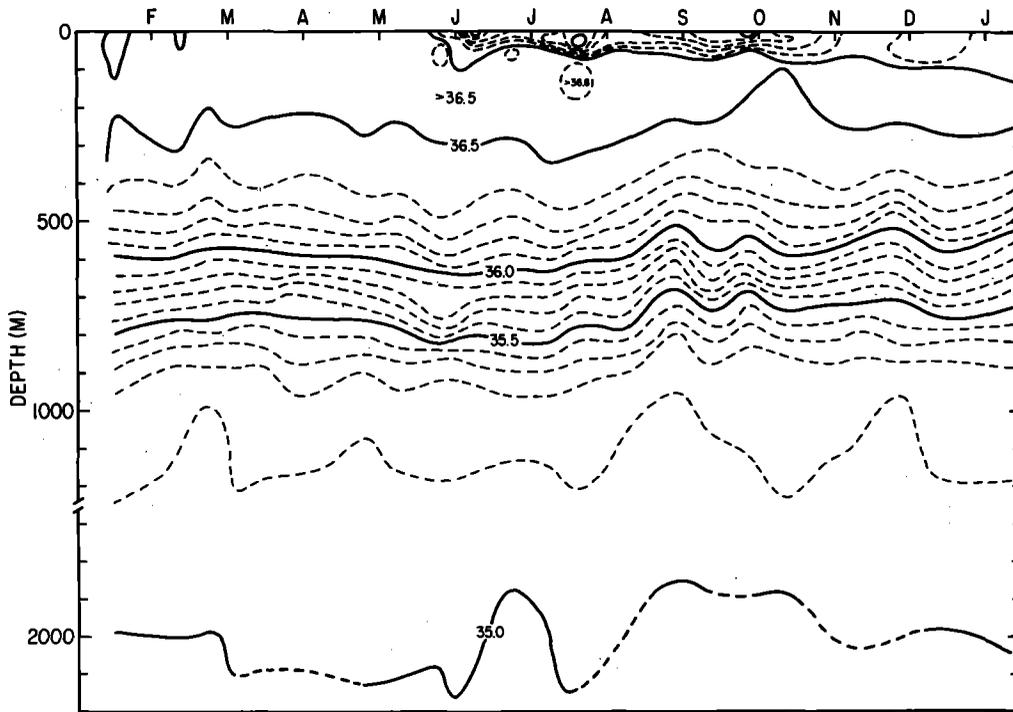
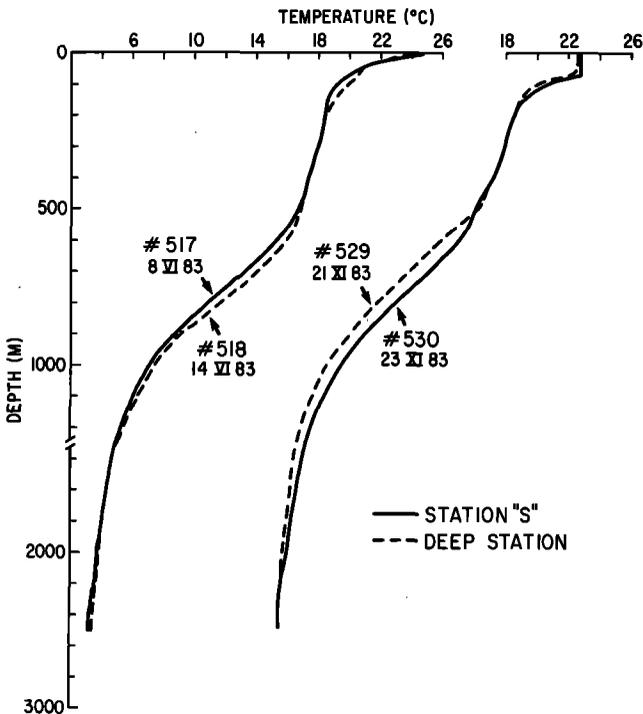


Figure 8.3. Salinity (‰) from Stations 507 to 532 (January-December 1983) plotted against time.



The three deep stations were occupied on 23 February, 14 June and 21 November. In each case a regular station was made within a few days. In February the deep and regular stations were very similar; differences in isotherm depth through the thermocline occurred in June and November (Fig. 8.4) but they do not appear to be significant: the depth differences are less than 50 m, comparable to normal fluctuation at Station 'S' and the offshore station has a deeper thermocline in June and a shallower one in November.

Figure 8.4. Temperature vs. depth traces comparing Station 'S' with offshore stations on similar dates.



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WRIGHT, W.R. and KNAP, A.H. 1983. Hydrostation 'S' off Bermuda in 1982. In: *Time series of ocean measurements*, vol. 1. IOC Unesco Technical Series No. 24.

## Acknowledgements

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# 9. Monthly Maps of Sea Level in the Pacific during the El Niño of 1982 and 1983

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## Introduction

Variations of the topography of the sea surface occur on many time and space scales. They range from the tides on the high-frequency side of the spectrum to the very slow changes of sea level caused by the movements of tectonic plates and changes in the volume of water in the ocean basins. Between these two extremes is a whole spectrum of less dramatic sea level variations that are related to the weather, to ocean dynamics, to the annual cycle and to short-term climatic variations. It is this part of the spectrum on which our attention will be focused.

In the frequency range from weeks to years the topography of the sea surface is related to ocean circulation by geostrophy; consequently, sea level differences are a measure of the intensity of the various branches of ocean circulation. Sea level can also document large-scale wave processes, such as planetary waves, and some will be obvious from the data presented in this report. Sea level is also a measure of other oceanographic parameters, like heat content or thermocline topography, the latter especially in the tropical ocean, where the density structure can be approximated by a two-layer system. Sea level also is an important tool in the study of water budgets over large areas and in particular of the warm water sphere.

## Data

During 1974/75 a network of sea level stations was established on islands in the Pacific to monitor sea level variations (Wyrski, 1979a). Data from the 27 stations of this network are used together with data from 8 island-based stations operated by the National Oceanic and Atmospheric Administration (NOAA) and several stations along the west coast of America. Experience has shown that large-scale events with time scales from months to years can be conveniently documented by the use of monthly mean sea level data (Wyrski, 1979b). The monthly mean values of sea level height (SLH) observed at each station were not corrected for atmospheric pressure because the variability of monthly mean atmospheric pressure is small in the tropical ocean and because there it is largely uncorrelated with sea level in the spectral range of interest (Roden, 1963; Luther, 1982).

Because most of the sea level stations used in this study have only been in operation since 1975, all data have been referred to the mean sea level (MSL) at each station for the seven-year period 1975 to 1981. No trends have been removed because of the shortness of this period; in view of the presence of short-term climatic fluctuations with periods of several years, the identification and

removal of a trend requires data over several decades. Almost all stations show a weak annual cycle, which has been documented by Wyrski and Leslie (1980). At most stations in the tropical Pacific the amplitude of the first harmonic of the annual cycle is less than 50 mm and would be apparent in charts contoured at that interval. Consequently the mean annual cycle (MAC) for the period 1975 to 1981 has been computed for each station and has been removed from the sea level values. This procedure results in monthly mean sea level anomalies (SLA), which are defined by the relation

$$SLA = SLH - MSL - MAC.$$

Maps of sea level anomaly for each month of the period 1982 and 1983 are shown in Figs. 9.1 to 9.24.

The accuracy of sea level observations from well-tended gauges is relatively high, and values between 10 and 20 mm are usually quoted for the accuracy of monthly mean values. This value of the accuracy of the measurements might be viewed in relation to the data noise resulting from local processes influencing each station. A comparison of nearby stations within a few hundred kilometres shows that the root-mean-square differences of monthly mean sea levels between stations are about 30 mm. This value is, of course, larger than the accuracy of the measurements but smaller than the standard deviation of monthly mean sea level at a given station, which is typically 50 mm (Wyrski and Leslie, 1980). Consequently, a contour interval of 50 mm has been selected for the monthly maps of sea level anomaly. Deviations in excess of this value must be considered significant.

## Sea Level Anomalies during the 1982-1983 El Niño

From January to June 1982, sea level anomalies over most of the equatorial Pacific are relatively small. In January a positive anomaly of up to 120 mm is developed in the area of the Marina and Caroline Islands and a negative anomaly around the Hawaiian Islands(1). This implies a decreased flow in the North Equatorial Current. Sea level in the Gulf of Panama and along the coast of Ecuador is above normal and stays above during the first half of 1982. In February a positive sea level anomaly develops in the area between the Solomon Islands, New Caledonia and Tahiti. It connects with the

(1) For the location of the various islands etc. mentioned in this section see Figure 9.25.

anomaly around the Caroline Islands, which has weakened slightly. By March almost the entire western equatorial Pacific has above normal sea level, but the anomalies exceed 100 mm only in a few locations. The negative anomaly around the Hawaiian Islands is still present. In April and May a strong negative anomaly appears at Johnson Island with a value of -241 mm in April. Sea level at Johnson Island is known to be highly variable over periods of a few months. These abrupt changes of sea level are probably related to north-south displacements of the axis of the North Equatorial Countercurrent or to the passage of large eddies, but their true reason has not yet been studied. Also, in April sea level along the Caroline Islands drops and a negative anomaly develops, indicating a deepening of the Countercurrent trough and a simultaneous intensification of both the Countercurrent and the North Equatorial Current. The positive anomaly along the equator and between the Solomons and Tahiti remains. The pattern is essentially the same during May.

In June a negative anomaly stretches from Hawaii to the Philippines and positive anomalies are found at the equator and in the area between Fiji and Tahiti, but values reach 100 mm at a few locations only. This pattern changes drastically in July, when a strong negative anomaly with a peak value of -179 mm develops in the area of the Caroline Islands. At the same time sea level rises along the equator from Nauru to Christmas Island. This change, which occurs in response to the appearance of westerly winds over the western equatorial Pacific (Sadler and Kilonsky, 1983a), signals the start of the 1982-83 El Niño.

The anomaly pattern suggests a very strong flow from west to east between the equator and 8°N, which is probably part of the equatorial Kelvin wave generated by the onset of the westerly winds. A similar but weaker gradient in the sea level anomaly field exists to the south of the equator. In August both anomalies have intensified. In September the negative anomaly reaches from the Caroline Islands to Hawaii and has a value of -203 mm at Ponape. Sea level at Christmas Island is now 272 mm above normal, indicating the passage of a peak in sea level. A first substantial increase of sea level at the Galapagos Islands can be noted and indicates the arrival of the Kelvin wave.

In October sea level at the Galapagos Islands has risen to 235 mm above normal and at the coast to 288 above normal, while it has started to drop at Christmas Island. The negative anomaly in the western Pacific has increased further and has spread into the area of the Solomon Islands. The pattern of sea level anomaly in the central Pacific indicates an anomalous eastward flow on both sides of the equator with considerable meridional extent. It resembles extremely well the pattern of the thermocline anomaly simulated by McCreary (1977) with a simple two-layer model. Essentially the same pattern is found in November, but for the first time the sea level anomaly is as strong south of the equator as it is north of it. A positive anomaly of 215 mm has reached Callao and one of 173 mm has reached San Diego, indicating the poleward spreading of the sea level disturbance.

By December the sea level anomaly at the Galapagos Islands and at the coast has reached almost +40 cm, and anomalies in the western Pacific are -25 cm. The pattern is clearly developed, showing a drain of water from the western

equatorial Pacific, in particular from north of the equator, and an accumulation of water along the eastern side of the Pacific, in particular near the equator. The zero line seems to run north-south along about 150°W. Only in the southwestern part of the observation area, near New Caledonia and Fiji, does a weak positive anomaly remain. The arrival of the first peak of sea level at the Galapagos Islands and the simultaneous draining of warm water from the western Pacific eliminate the usual east-west slope of sea level along the equator (Wyrtki, 1984b).

The pattern of sea level anomaly in January 1983 is essentially the same as in December 1982, except that the negative anomaly in the western Pacific to the north of the equator has decreased in strength. In February this decrease continues, but south of the equator the negative anomaly increases considerably to over 200 mm from the Solomon Islands to Penrhyn. This increase is apparently in direct reaction to westerly winds over that area during January and February (Sadler and Kilonsky, 1983b). At the eastern side of the ocean the sea level anomaly at La Libertad is highest (438 mm) in January. Also at Callao and at Buenaventura the anomalies are highest in January. In February these anomalies decrease substantially as the warm water accumulated in the eastern Pacific by the Kelvin wave departs from the equator poleward or is reflected westward.

In March an entirely new development emerges. Whereas the sea level anomaly in the western Pacific north of the equator has decreased substantially, the negative anomaly south of the equator continues to deepen. This deepening continues in April, when negative anomalies of more than 200 mm stretch from New Guinea to Penrhyn with a deepest value of -414 mm at Funafuti. This huge anomaly extends south as far as Tahiti and New Caledonia, north as far as the equator and stretches east to west over a distance of about 8000 km. Winds over the sea level anomaly are generally weak, but extremely anomalous. Between the equator and 10°S where trade winds are expected to blow, winds are actually from the west, and between 10°S and 20°S, where weak wind would be expected, trade winds were actually blowing. This southward shift of the trade wind belt apparently results in the sea level anomaly. The anomalous topography of the sea surface itself also indicates an anomalous development of geostrophic flow. Between the equator and 10°S and anomalous eastward flow is indicated, and between 10°S and 20°S an anomalous flow to the west. The sea level anomaly near 10°S seems to represent a southward displacement of the subtropical gyre of the southern hemisphere in response to the changed wind system (Wyrtki, 1984b).

Between February and April 1983 winds over the equatorial Pacific are very weak, which leads to an elimination of the usual east-west slope of sea level (Wyrtki, 1984b). Although zonal winds increase again in May, the restoration of the normal east-west slope takes several months.

In May and June the first signs of a positive anomaly appear along the Countercurrent near 7°N, indicating a filling of the Countercurrent trough which implies a weaker North Equatorial Current and a weaker Countercurrent in the western Pacific. The large negative anomaly near 10°S retains its strength during May and June. Sea level at Funafuti remain 400 mm below normal from April to

June, and the area of negative anomalies remains unchanged. On the coast of South America a second peak in sea level is reached in May and is at high as the previous peak in January; thereafter sea level drops fast. This second peak is probably in response to the strong westerly wind anomaly which, from March to May, lies over the area between the equator and  $10^{\circ}$  S and from the date line to  $100^{\circ}$  W (Arkin *et al.*, 1983). During this period several hurricanes hit Tahiti and the Marquesas Islands (Sadler and Kilonsky, 1983b).

During July and August the positive sea level anomaly along the coast of South America decreases fast and by September it disappears. The negative sea level anomaly near  $10^{\circ}$  S in the western Pacific also decreases, but much more slowly. It shrinks in size and amplitude, but sea level in the Solomon Islands is still 312 mm below normal in August. This indicates a very slow recovery to the normal situation, in spite of the fact that winds over the anomaly during June, July and August are virtually normal (Arkin *et al.*, 1983).

During the remainder of 1983 the negative sea level anomaly in the western Pacific near  $10^{\circ}$  S slowly decreases, but is still apparent in November. The positive anomaly along the Countercurrent trough near  $10^{\circ}$  N, which developed in

May, expands in October and November and shifts northward. By December 1983 the very strong sea level anomalies have disappeared, but sea level is still below normal along the entire equator, indicating a loss of warm water from the equatorial Pacific as a result of El Niño (Wyrtki, 1984c).

The 24 monthly maps of sea level anomaly shown in this report provide clear evidence of the very large scales of sea level response during El Niño, of the horizontal coherence of sea level fluctuations and of their long time scales. These maps attest to the fact that sea level is an excellent parameter for the monitoring of large scale changes in the ocean and for the study of their dynamics.

## Acknowledgements

I wish to thank Ted Murphy for maintaining the sea level stations, Brent Miyamoto for processing the data and Shikiko Nakahara for preparing the maps. This work has been supported by the National Science Foundation under grant OCE-82-13486. This support is gratefully acknowledged.

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Figure 9.1-3. Sea level anomaly (SLA) in millimetres in the Pacific Ocean in January, February and March 1982.

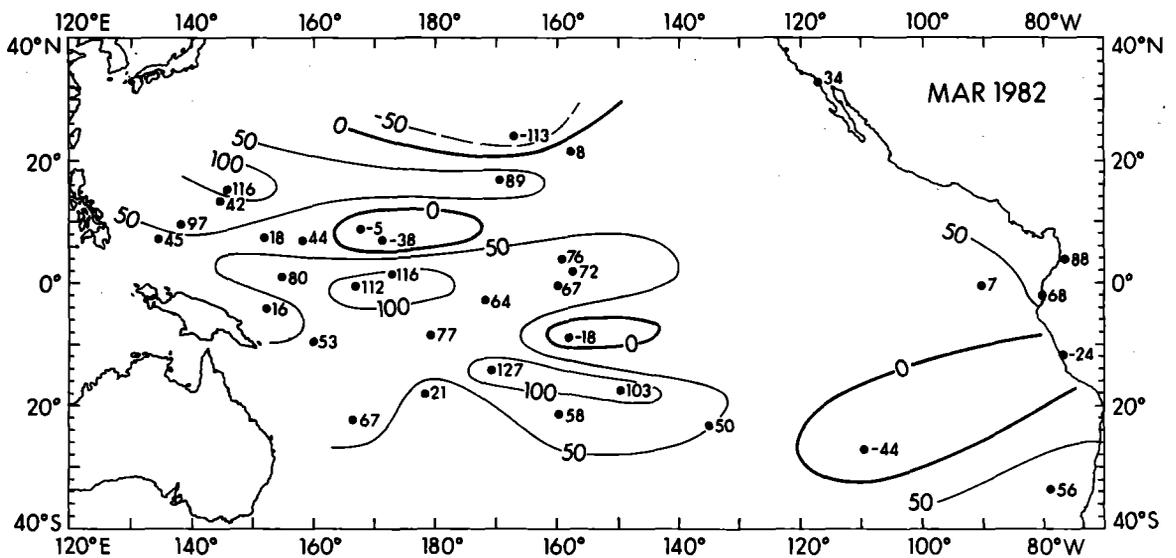
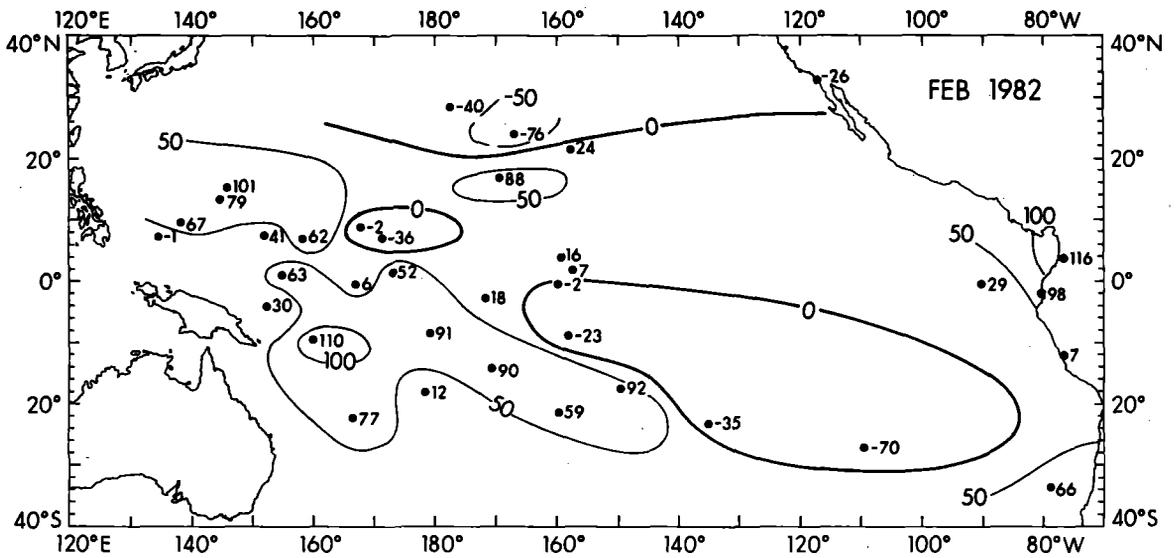
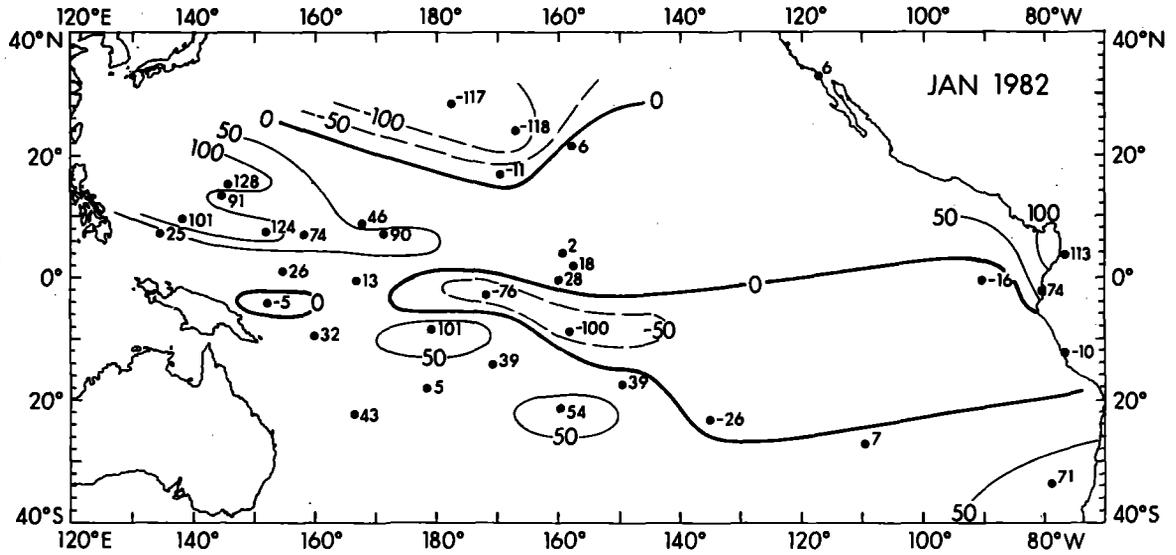


Figure 9.4-6. Sea level anomaly (SLA) in millimetres in the Pacific Ocean in April, May and June 1982.

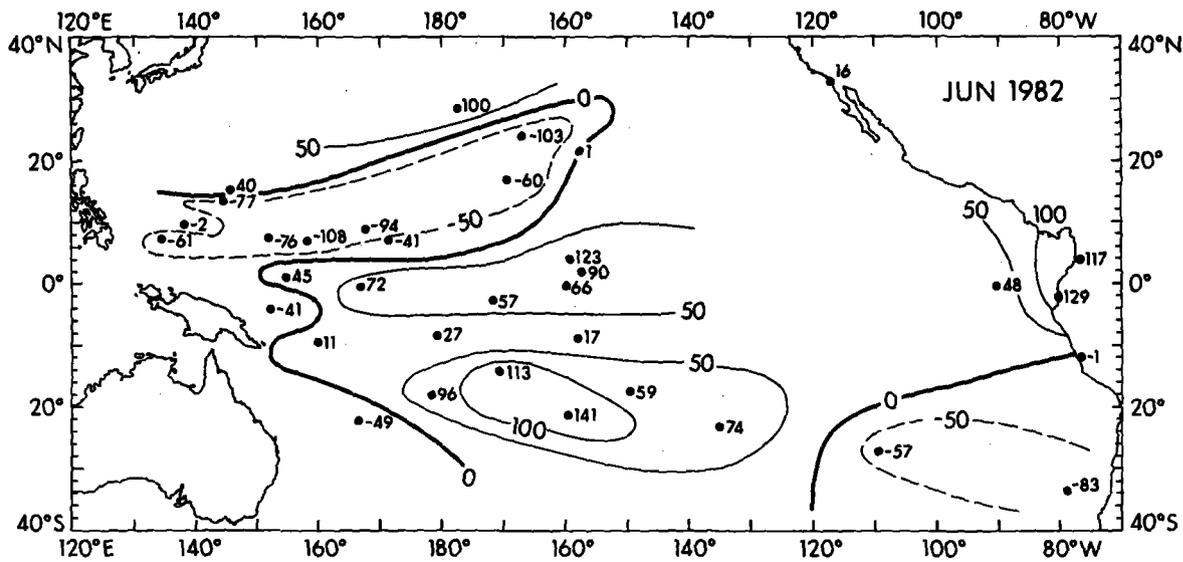
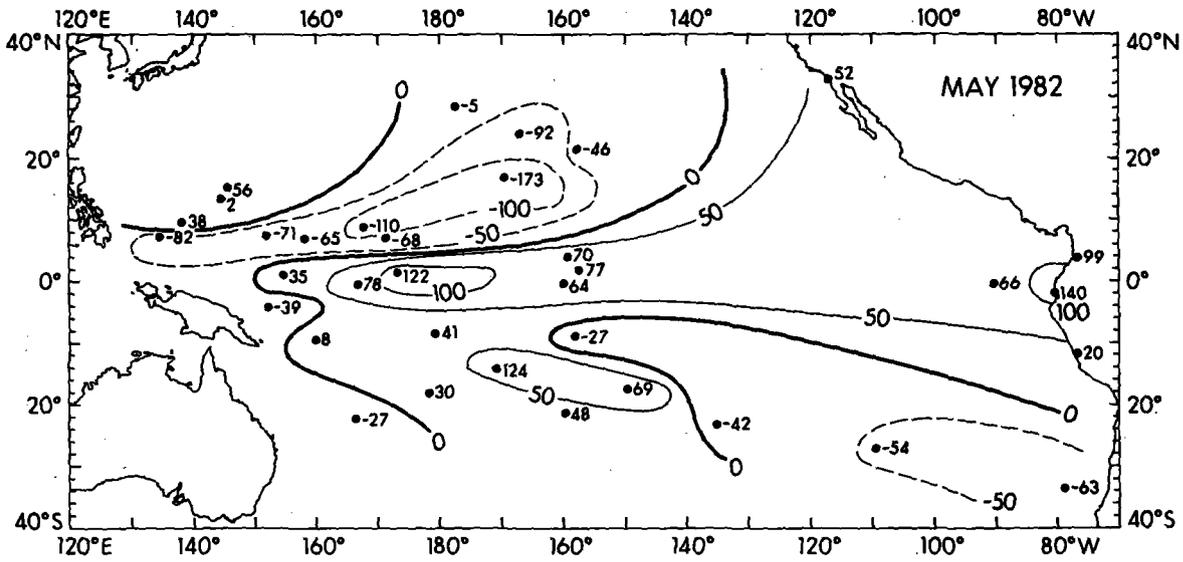
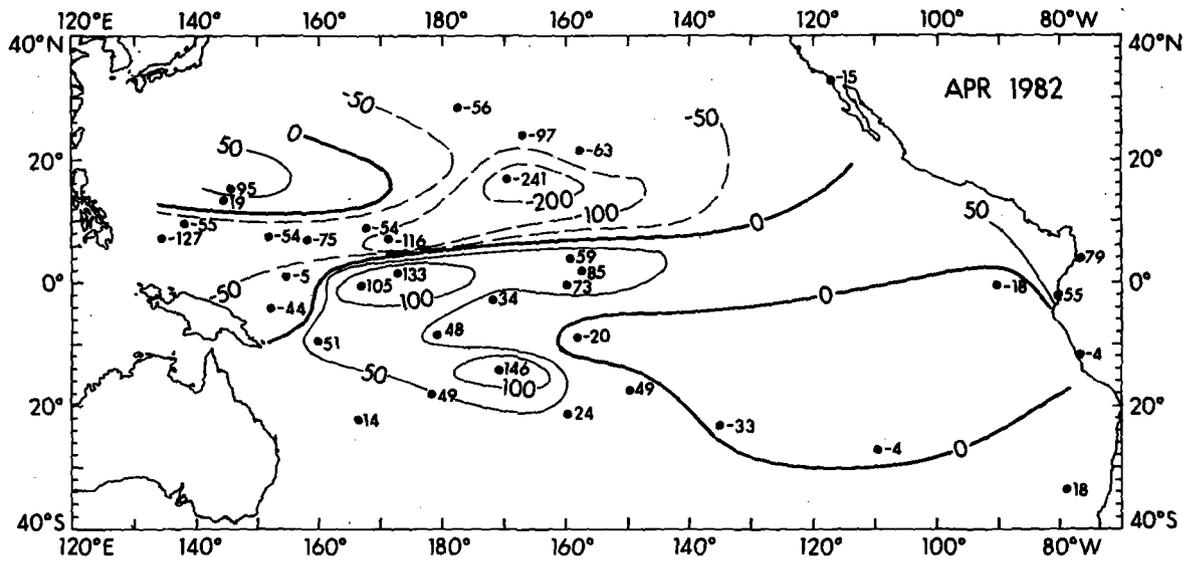


Figure 9.7-9. Sea level anomaly (SLA) in millimetres in the Pacific Ocean in July, August and September 1982.

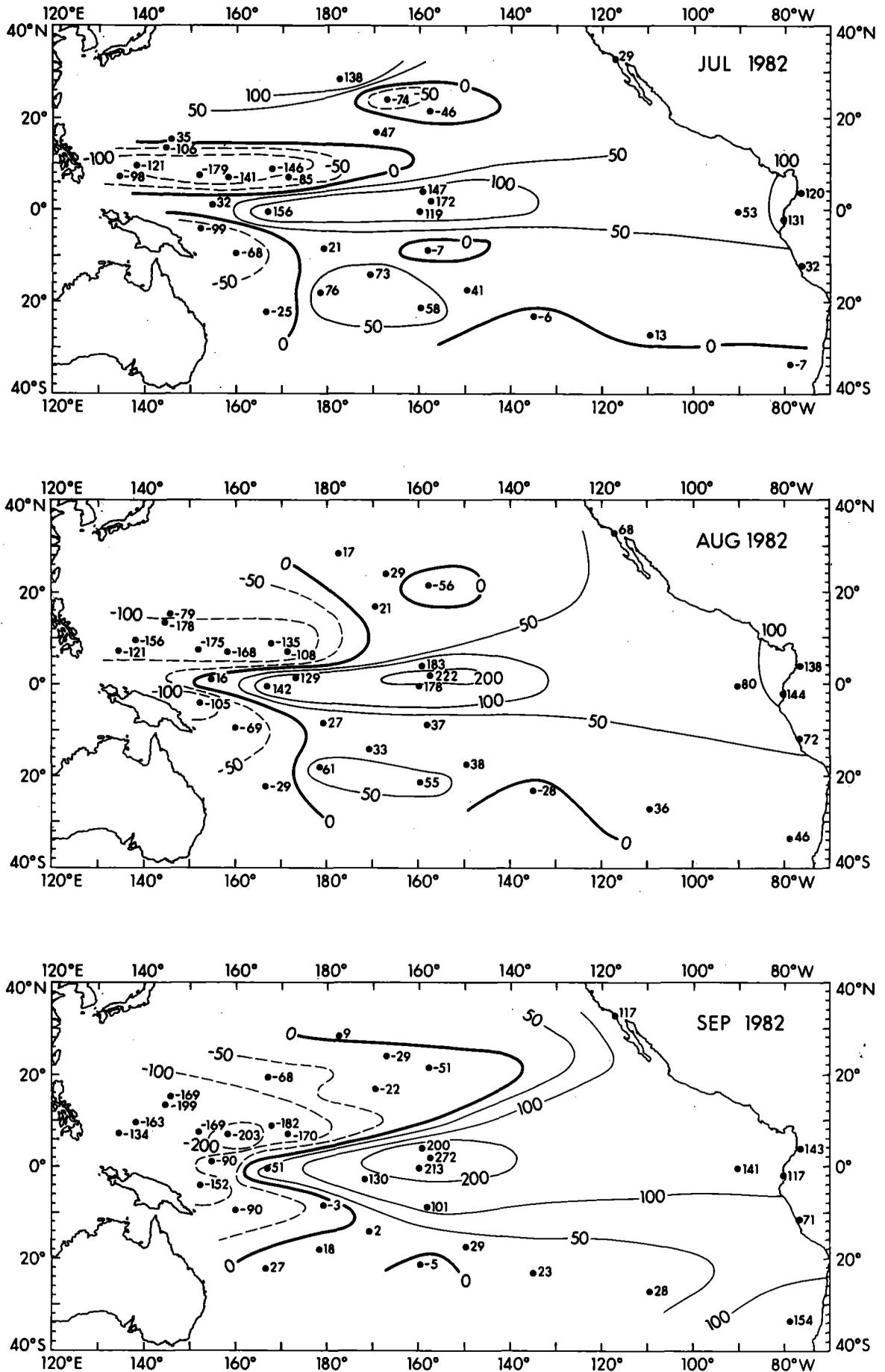


Figure 9.10-12. Sea level anomaly (SLA) in millimetres in the Pacific Ocean in October, November and December 1982.

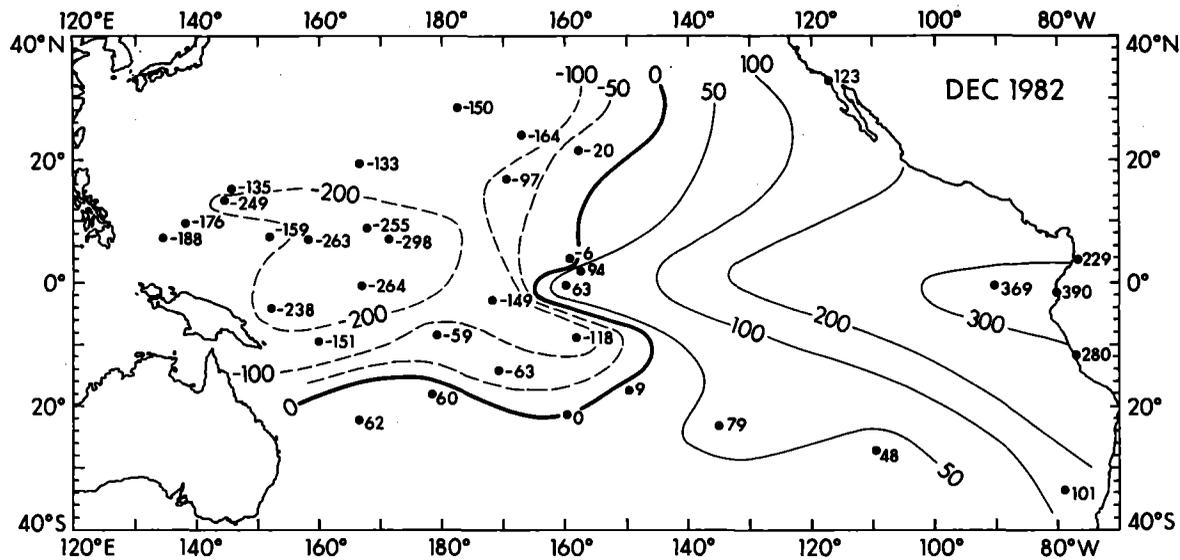
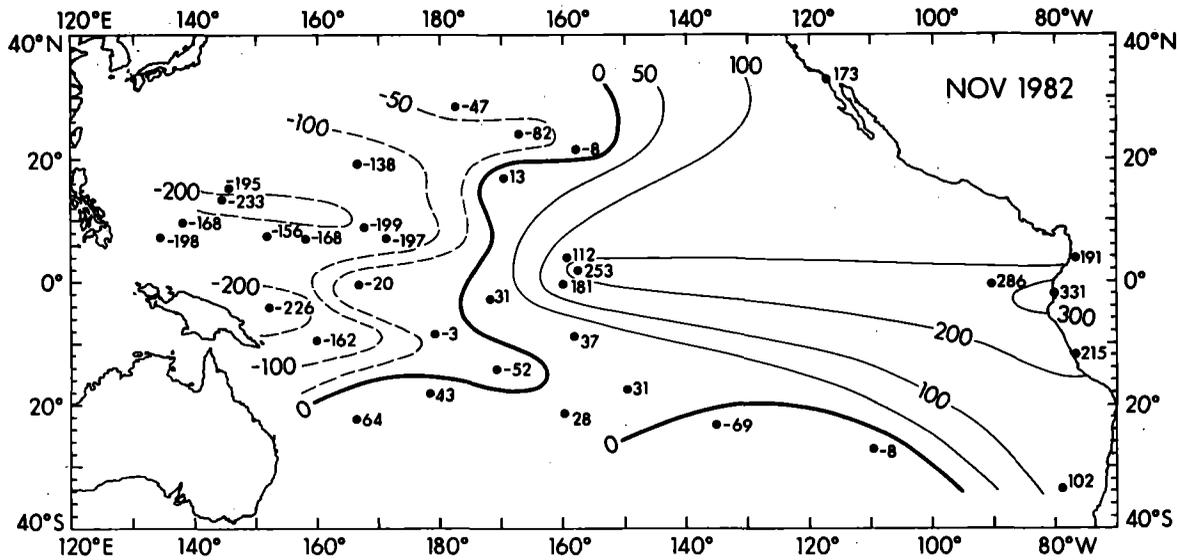
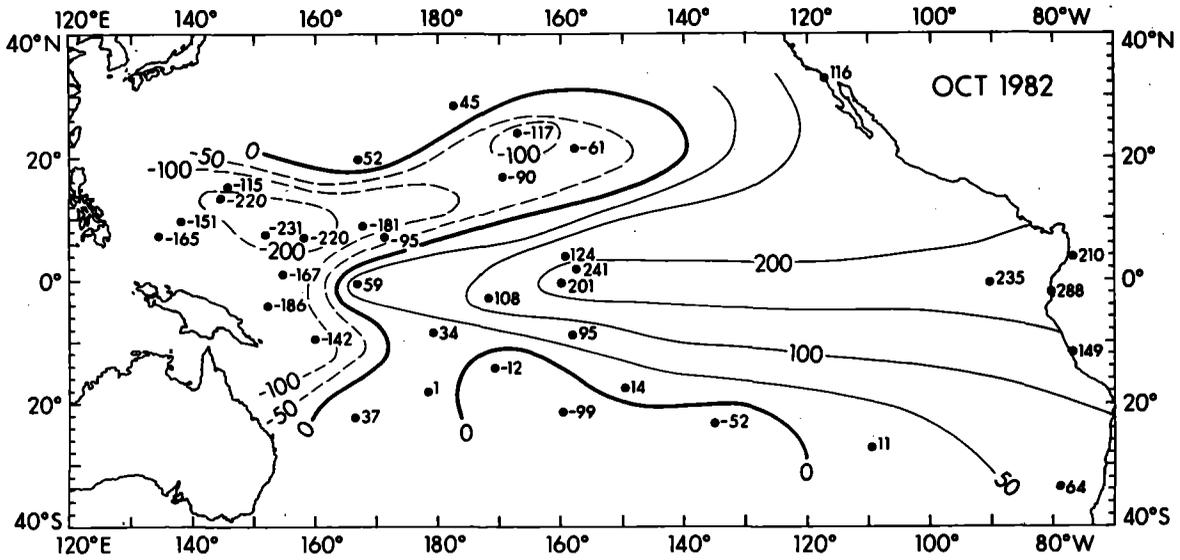
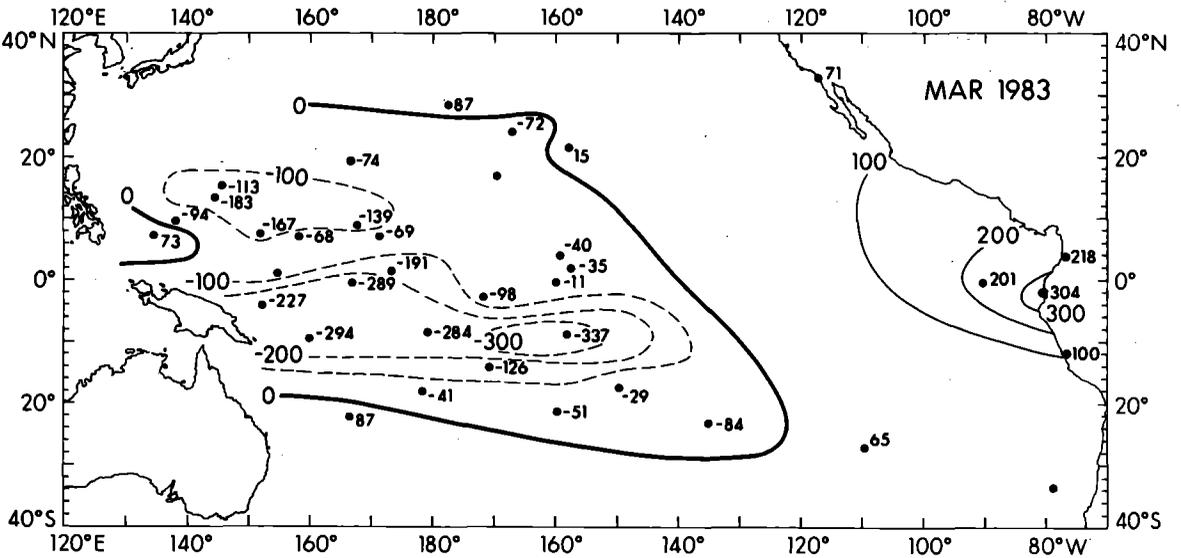
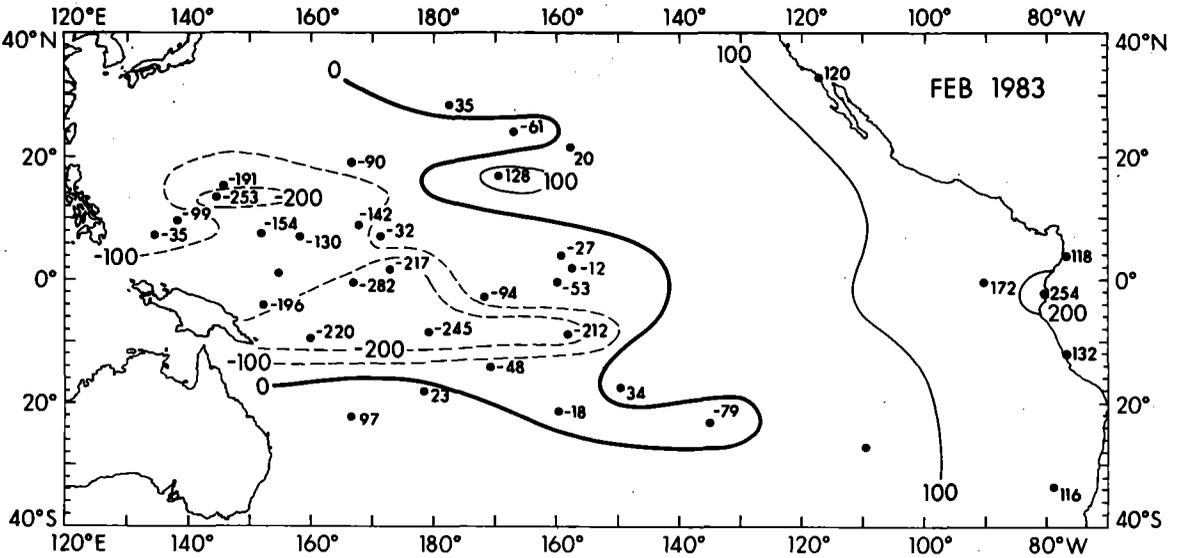
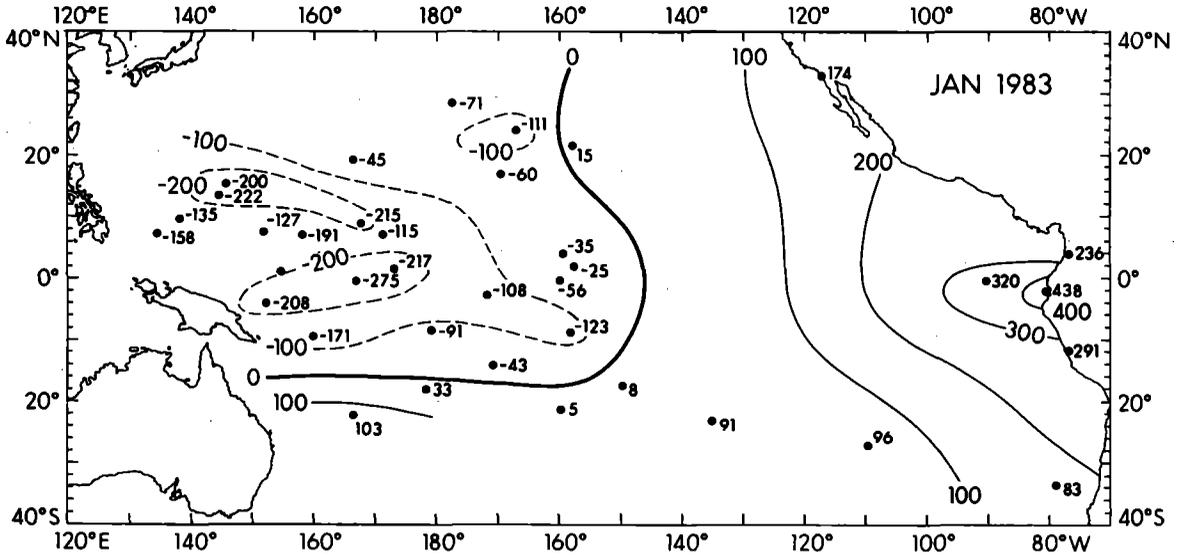


Figure 9.13-15 Sea level anomaly (SLA) in millimetres in the Pacific Ocean in January, February and March 1983.



**Figure 9.16-18. Sea Level anomaly (SLA) in millimetres in the Pacific Ocean in April, May and June 1983.**

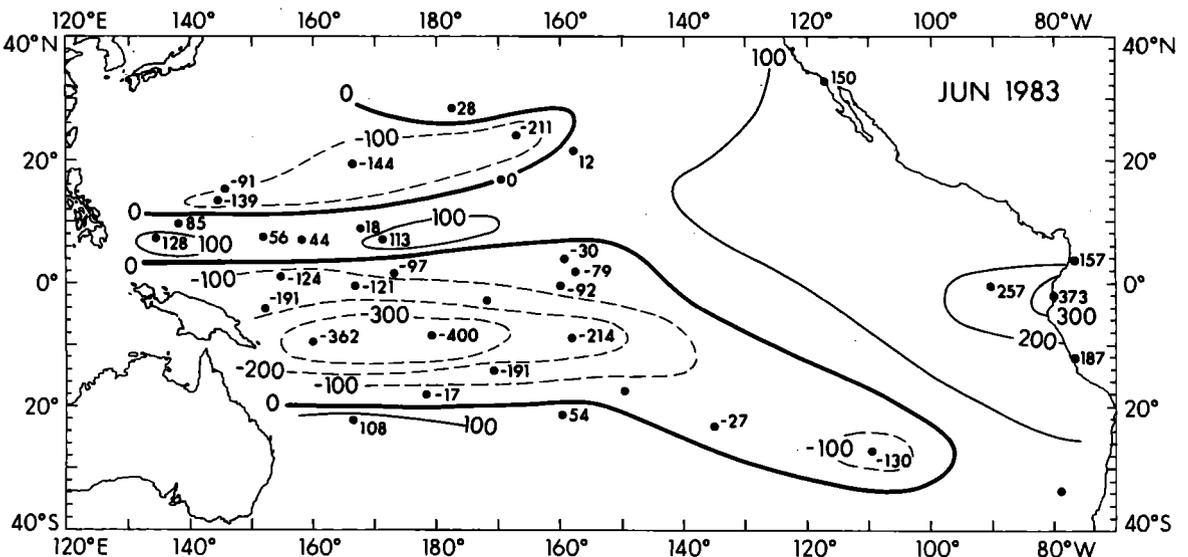
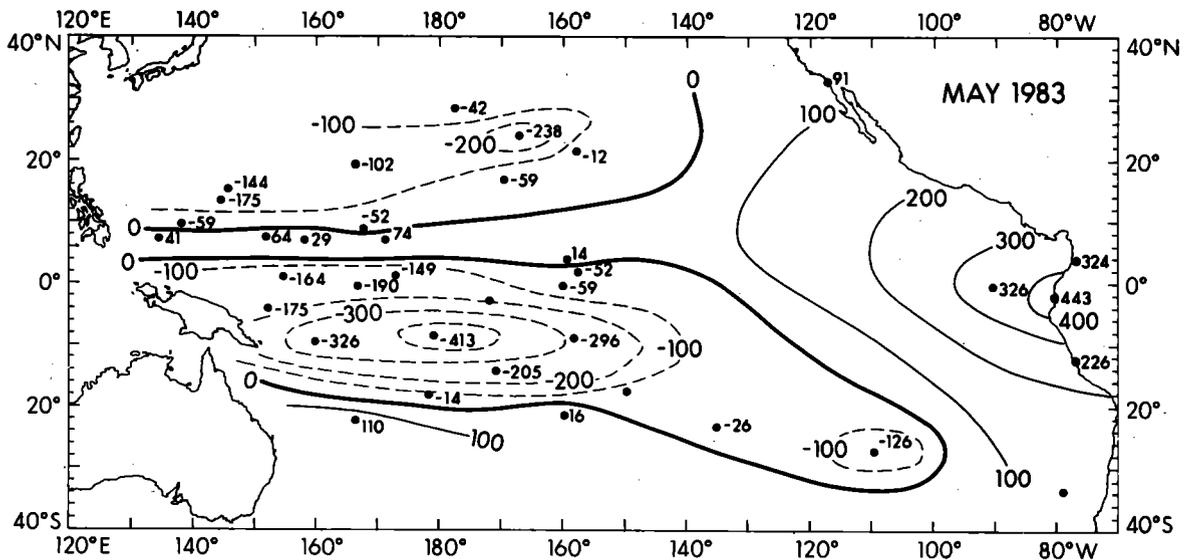
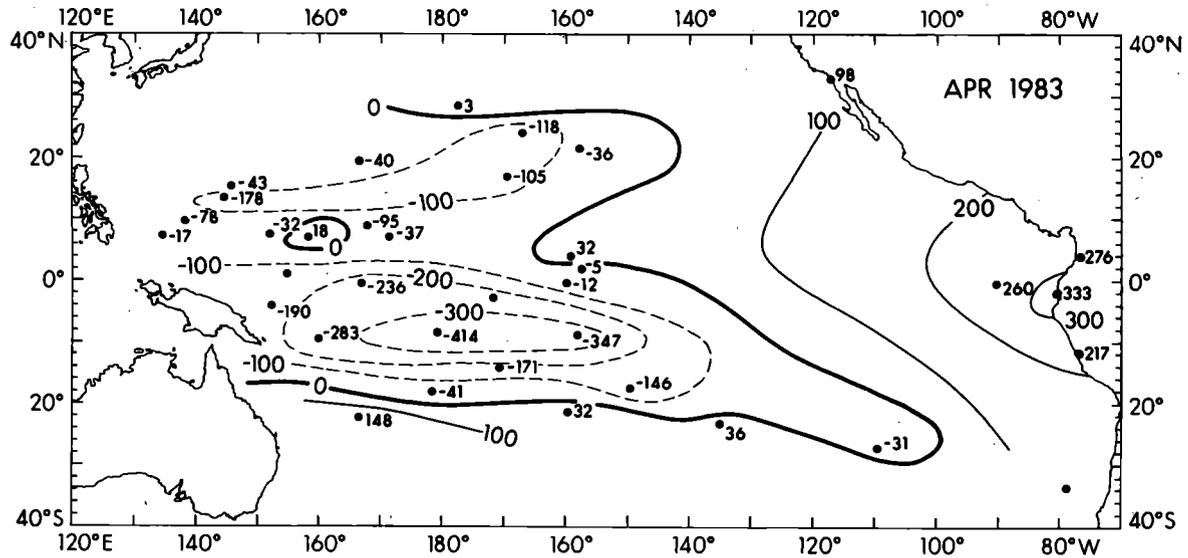




Figure 9.22-24. Sea level anomaly (SLA) in millimetres in the Pacific Ocean in October, November and December 1983.

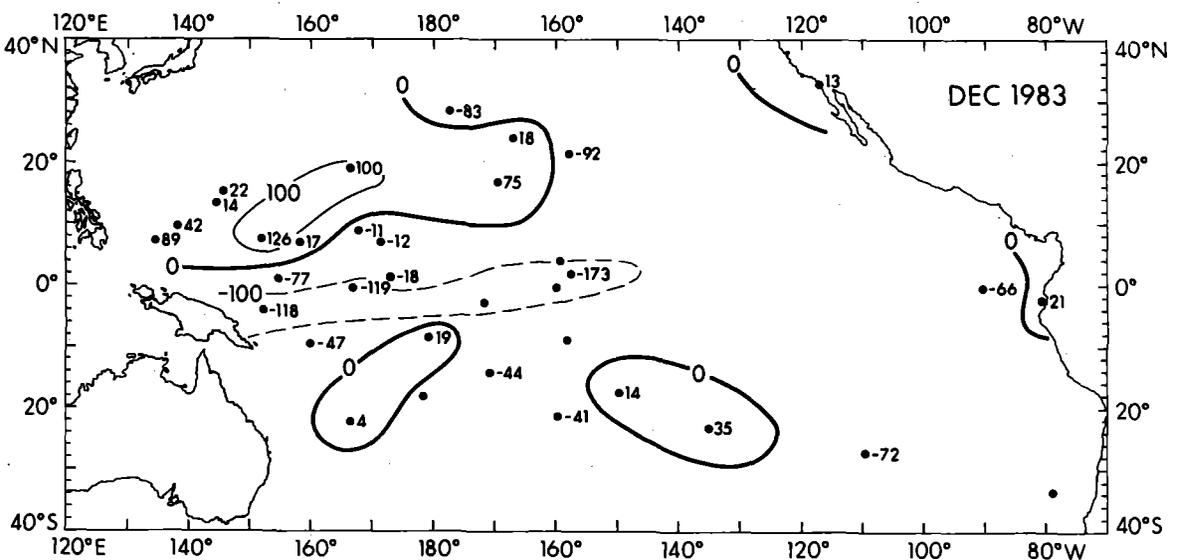
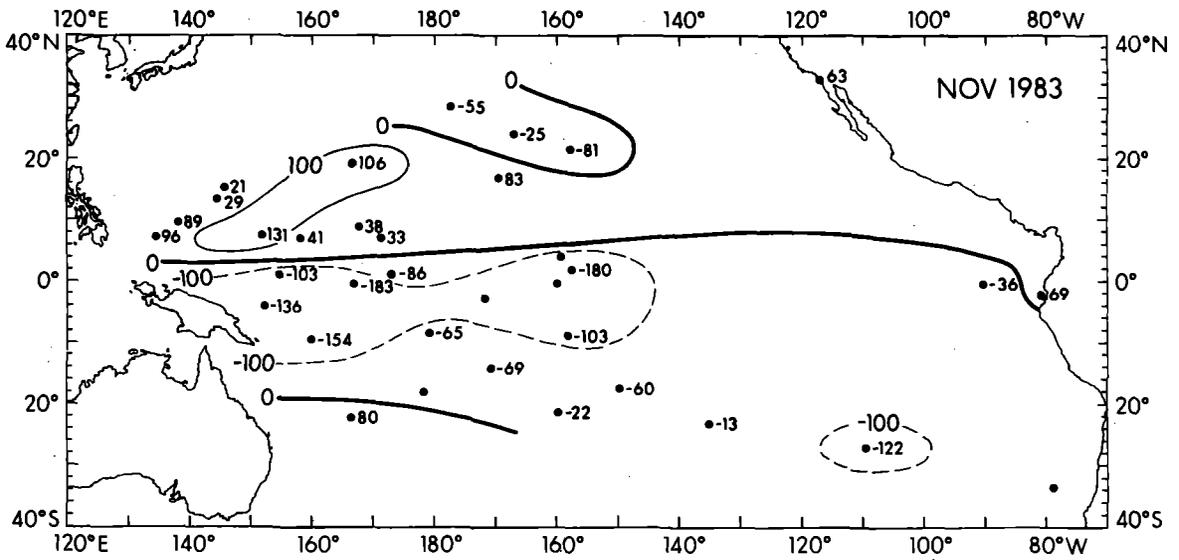
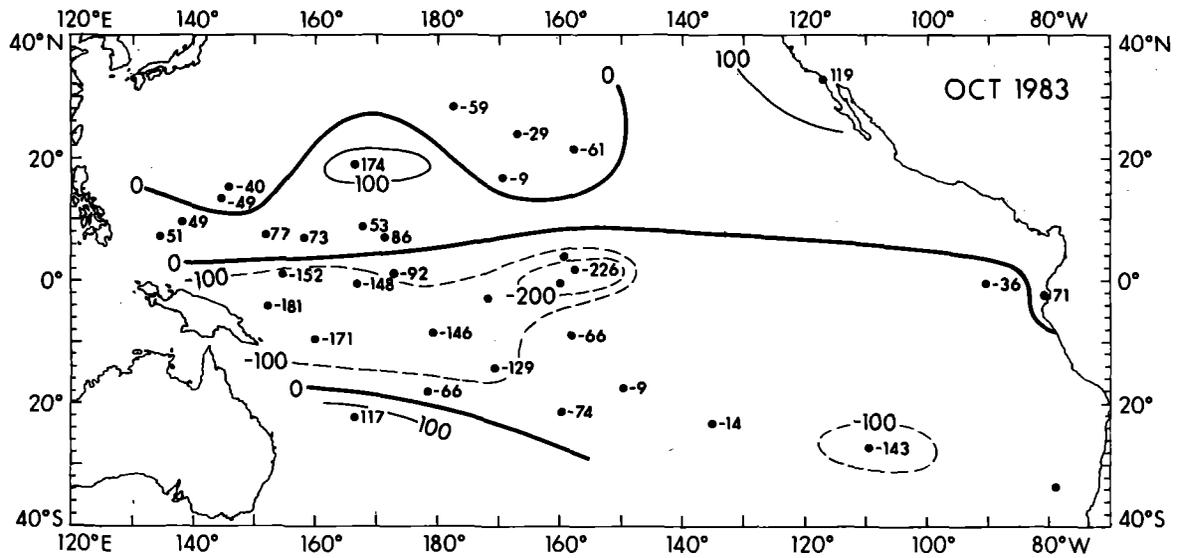
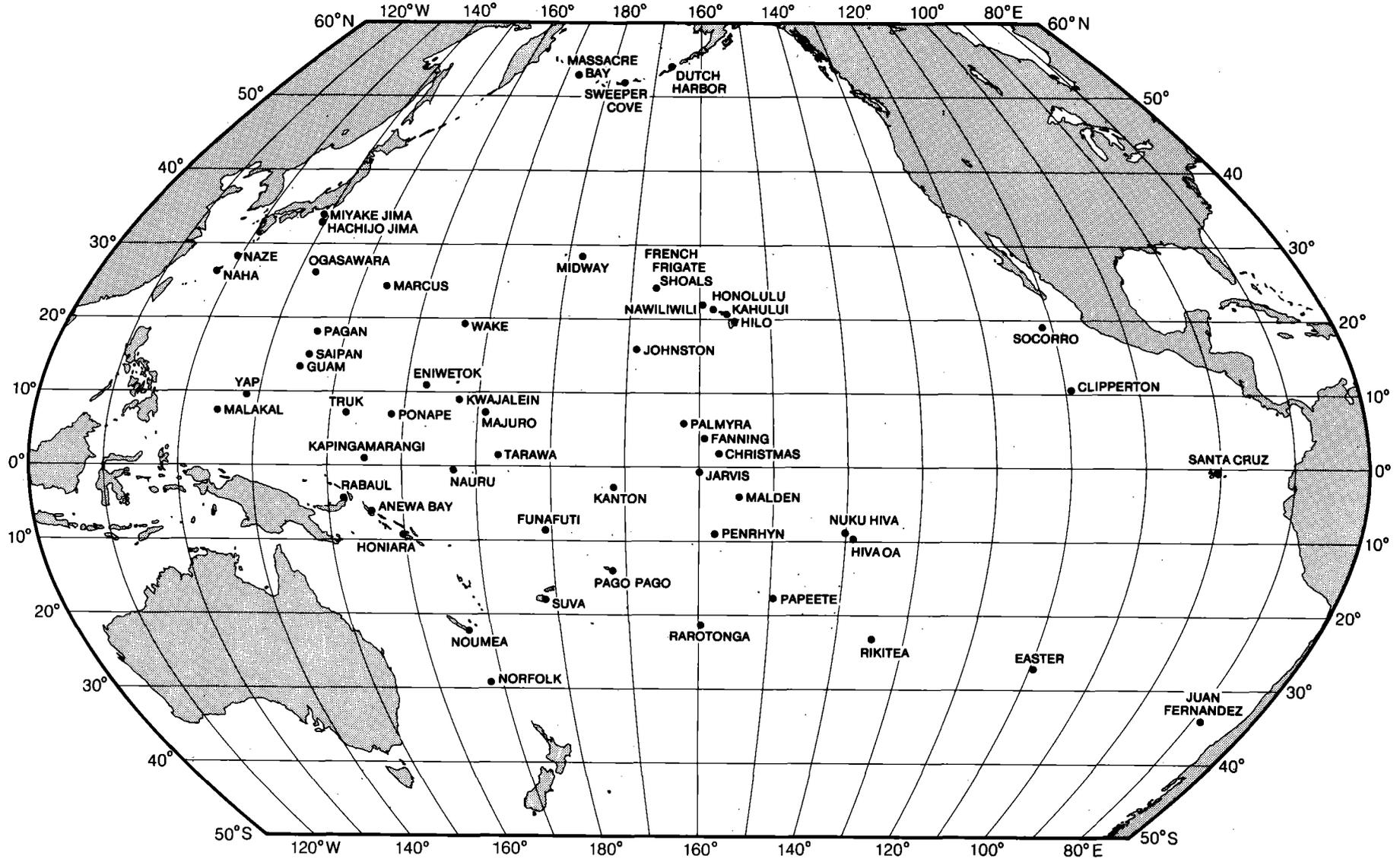


Figure 9.25. Island sea level network.



# 10. Specific Problems in maintaining Time Series Observations

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Although the need for long oceanic time series for use in climatic studies is generally recognized, a programme of undertaking the continuous observations is not as easy as is usually assumed. There is relatively little problem in initiating a programme but there are considerable difficulties in maintaining the series, and each time series carries its own set of problems. Some of these are common to all geophysical time series measurements while others are unique to observations at sea. They fall into the following main categories:

1. Funding
2. Selection and training of observers
3. Equipment and instruments
4. Logistics
5. Liaison
6. Quality-control of data and data processing
7. Others

Most of the problems are interrelated; for example, problems with equipment and instruments can frequently be traced to poor quality equipment or poor selection and training of observers, both of which, in turn, may also be due to underfunding.

## Funding

Inadequate funding is the main difficulty faced by most organizations running time series programmes. Closely related to this is the lack of agency commitment to such a long-term programme. Practically all problems mentioned below can, indeed, be traced either directly or indirectly to funding. There is a constant fear that funds will eventually be cut off. This is especially true for programmes which involve the use of ships to conduct the observations, as rising fuel and food costs make the operation of oceanographic vessels increasingly costly.

For most research-oriented organizations, funds for monitoring the ocean come from the same general allocations as for conducting research projects. Inasmuch as the process-oriented programmes are finite in contrast with the open-ended monitoring programmes, it is reasonable to favour the former which can usually produce results relatively shortly after the inception of the programme. By its very nature, the significance of a long time series does not become apparent until after an appreciable lapse of time. For this reason it can

be difficult for managers and even scientists to justify the continuation of such a series. Compounding this can be the introduction of such managerial innovations as "zero-based budgeting" which can make the yearly justification of continuing long time series even more difficult.

Certainly, grant-dependent universities would have difficulty in undertaking a programme of long time series as a continuing proposition, simply because of its length. Nor would the private sector be likely to embark on such studies, given the length of time needed before a tangible result could be produced. This leaves the federally-funded organization as the only body that can effectively undertake a programme of long time series. It is hardly surprising, therefore, that most long-term measurements of such parameters as river discharges, precipitation and air temperature are supported by Federal Funds in most countries.

If obtaining the necessary funds to conduct long oceanic time series observations in developed countries is difficult, consider the case of the developing nations which have other demanding priorities. For example, there have been cases where even simple observations such as sea-level height measurements have ended shortly after the States have achieved their independence. The problem is greater for States that are politically unstable. There, even when measurements were continued, changes in governments have resulted in loss of data due to changes in bureaucracies, relocation of administrative offices and personnel, and changes in observational methods.

## Selection and Training of Observers

An agency running a programme of time series observations and providing its own observers can select candidates who are best suited for making the observations. Under ideal conditions it would select well-motivated, careful, patient, persevering, healthy individuals of above-average intelligence, who would not be prone to sea sickness and who would not easily become weary of making sustained, repetitive measurements over a long period of time. Given sufficient time for recruiting, such individuals can be found, but more often than not new recruits have to be found quickly to replace those lost from the programme so that the programme can continue without interruption. Well-trained observers, especially those having the necessary qualifications for sea duty, are not readily available and as a result hastily-recruited, less-than-qualified observers have to be hired as substitutes, and this may result in the deterioration of data quality.

Most ocean time series measurements, however, involve special or "voluntary" observers who happen to be on platforms or sites where observations are to be made and who have specific duties other than making oceanographic observations. They may be ships' officers or crew members, lighthouse keepers, meteorological or telecommunication technicians, caretakers of buildings on remote islands, etc. These are observers over which an agency running a time series programme has little influence, except perhaps to provide them with limited training. They may range from a very co-operative and enthusiastic observer to an unruly, disinterested individual and, in some isolated cases, an unco-operative person. There is little that an agency can do about this, except perhaps mention to their superior in a diplomatic way that a more suitable person would be a welcome alternative.

Happily, such instances are rare. Many of these observers take on the new tasks of making oceanographic observations with enthusiasm and welcome the new jobs to ease the boredom that may be present in their main duties. Even complicated methods of measurement with sophisticated instruments are frequently taken on as challenges. On the other hand, a few regard the new tasks as an unnecessary burden and make observations with some reluctance. Such cases are however an exception.

A programme of ocean time series measurements is usually undertaken with a minimum of resources. This can create a problem. Within an organization there may be only a few technicians who are competent, familiar with the programme and well motivated. Because the programme is so tightly run, even a short absence of technicians due to personal reasons such as illness or vacation could be disruptive.

The training of observers for ocean time series measurements is not a problem if there are a limited number of observers who stay throughout the programme. During the initial stage of the time series observations the data may yield results that are sufficiently interesting to the scientists and technicians that warrant their continuity with the collection of reliable data. However, after that, the observations and related work (e.g. data processing) become tedious, repetitive and time-consuming and interest in the programme wanes for both scientific and technical personnel. And sometimes even those in the programme originally leave to pursue other jobs elsewhere. There is, therefore, a continuing problem of keeping the personnel involved well motivated. If they intend to stay with the programme it is to the agency's advantage to give the observers a breathing spell occasionally, by providing them with more attractive duties elsewhere.

In recent times, observers aboard ships-of-opportunity have tended to be the ones most likely to change. In some instances the turnover is so frequent that new recruits are being trained by a person who himself has just recently been trained hastily, perhaps during the course of a single field trip. Such a state of affairs does not readily lead to the acquisition of good-quality data.

While the observers are the most important link in the collection of time series data, providing

them with sufficient training is not always easy to do. In many instances ad-hoc training must suffice. With a change of the ship's crew, for example, a substitute may be assigned by the captain to collect the data. He may receive some preliminary instructions regarding the observations by the outgoing observer. But, in order to ensure that the new observer is making proper observations, the scientist in charge should take the time to visit the ship to provide him with proper instruction. Unfortunately, ship movements are not necessarily easy to predict, depending as they do on the availability of port facilities for loading and off-loading, with the result that considerable time may be taken up by the scientist in just 'chasing' the ship in order to meet the observers. When many ships are involved, as in the case of the ships-of-opportunity expendable bathythermograph (XBT) programme, the investment in time of the person running the time series programme can be considerable.

On a remote island, changes of personnel frequently result in communication and transportation problems. First, unless radio-communication is available, the change may not be apparent to the agency responsible for the programme until considerable time has elapsed. Then time is needed for instructions to be despatched. As it is best to make personal contact with the observer, the responsible person might find himself making a journey to the island just to provide proper instructions to this new observer. Such a journey may take several weeks if sea transportation is the only mode of travel available. This does raise the question of whether trips to ships and remote islands are really necessary. However, if proper data are to be obtained, it will be far more desirable to give instructions by first-hand contact rather than by mail or radiocommunication, because the objective of the programme and the scientific significance of the measurements can be conveyed to the observers so much more effectively by personal contact. Failure to impart such information usually results in the production of inferior data. In point of fact, when improperly-observed data are produced it is frequently the result of the failure of the scientific organization to impart clear, concise and understandable instructions on observational techniques and significance of measurements to the observers.

Besides communicating the objectives of the programme, the training should emphasize the care that must be exercised to obtain the data, the necessity of entering the pertinent information on data sheets, and above all, the importance of every single measurement that is to be made. Even in the case where very simple measurements such as the reading of bucket thermometers and the collection of surface bucket samples for salinity determinations are involved, adequate instructions must be provided so that the quality of data taken is consistently high.

An observer should know that a single crystal of salt could contaminate a salinity sample considerably and that a few drops of rain entering the sample bottle could significantly lower the salinity. Although these points may be obvious to an oceanographer, they are by no means obvious to the layman relied upon to make the observations.

## Equipment and Instruments

Even though a time series programme may be using the very best equipment and instruments available, the normal wear and tear that accompany the routine taking of observations over extended time periods makes the regular maintenance or replacement of this equipment necessary. Moreover, with many instruments frequent calibrations are required; even present-day reversing thermometers should be calibrated every few years. Funds must be set aside to keep the equipment and instruments in proper working order.

Time series measurements using automated instruments such as moored current meters are likewise subject to wear and tear. Not only are these instruments affected by corrosion, but they are also damaged by shipping, fishing activity and in higher latitudes by drifting icebergs.

The introduction of data-logging profiling instruments such as the salinity-temperature-depth (STD) recorder and conductivity-temperature-pressure (CTP) recorder has provided the oceanographer with much more detailed oceanographic structures than those obtainable by using conventional observational procedures. Moreover, these instruments are capable of making a cast in one-third the time taken for a Nansen bottle cast. These are indeed attractive features of the instruments, but some have been found to have instrument drift and are therefore not considered to be sufficiently reliable for time series operations. Frequent Nansen cast data are still required for field calibration. Although some time is saved during the operation, the drift in the instrument makes it difficult to process these data satisfactorily (more will be said about this later). Further, the addition of such instruments requires a full-time instrument-electronics technician to maintain them. Similarly, the introduction of minicomputer-interfaced data loggers to the XBT programme is a significant improvement to the subsequent analysis of XBT data, but a full-time specially-trained electronics technician is required to service the units. All of this adds further burdens to the existing budget.

To illustrate how sensitive the time series programme is to equipment failure, we may mention one example. When a winch failed during the occupation of one of the Panulirus stations, the sampling bottles, reversing thermometers and hydrographic wire were lost. It took about a year to get suitable replacement parts together in order to continue with the series--a loss of one year's data from a single accident!

## Logistics

Agencies conducting time series observations using their own vessels are having difficult times due mainly to the high cost of fuel. This is particularly a problem when observations are made far away from the home base of a research or survey vessel. An example of this would be the observations in Drake Passage or any part of the southern oceans conducted by agencies located in the northern hemisphere. A sizeable number of existing time series observations have been reduced in scope or even curtailed completely as a result of mounting costs of ship operation.

Where distance is the main problem, it would appear that perhaps more international effort is needed in the observation programme. For example in monitoring the ocean in Drake Passage some South American countries might be persuaded to contribute significantly to the observations.

Some of the simple logistical problems encountered at remote sites sometimes seem almost insurmountable compared with those closer to home. At Christmas Island, for example, a new observer had to travel by foot to the observation site because there was no other mode of transportation available. As a result, the sampling site had to be relocated in a more accessible place even though it was less than ideal from a scientific standpoint. Thus, seemingly unimportant matters may turn out to be very important from the standpoint of collecting time series data.

## Liaison

A very important part of the operation of long, ocean time series observations is the liaison between the scientists running the programme and analysing the results and the observers who make the repetitive measurements, often under trying conditions. To the observers who belong to the organization requiring the data, the objectives of the programme are easier to understand. For example, for global climate studies, or rational management of fisheries resources. However, as the time series extends in length and the observations continue on and on, such explanations become time-worn; as a result it becomes difficult to keep the observers motivated. This is in contrast to programmes involved in process-oriented studies in which the objectives are more clear-cut.

If the observations are made by special observers (ships' officers and crew, ship agent, lightkeeper, caretaker, etc.) liaison becomes even more important. These observers may be considered as unsupervised technicians in the programme and it is important to keep them well motivated by prompt and courteous response to their requests and complaints. Any errors in observational technique that become apparent must be dealt with quickly. This can be done by letter, telephone call or telegram message but nothing compares as favourably as a visit by the scientist supervising the programme. The more distant the observers are from the responsible agency running the programme, the more important this aspect of the programme becomes.

The former Pacific Oceanographic Group of the Fisheries Research Board of Canada at Nanaimo, B.C., routinely sent the officer-in-charge of the daily seawater observations to the observing sites - a move that was well appreciated by observers. And the scientist at the University of Bergen who runs the programme of time series observations at Station "M" also considers it necessary to send a scientist to the station every two years. This has almost certainly resulted in the flow of good data to the laboratory. In the case of observations from ships-of-opportunity, visits to ships when they arrive at port is almost mandatory in order to maintain good contacts with the observers. Moreover, it is essential that there should be a qualified person on hand when the ship arrives with the data.

In order to maintain the interest of the observers and others involved indirectly or

directly with the observations it is important to communicate as early as possible any interesting scientific results which utilized the data collected by the observers. In addition, any news item that has a bearing on the programme or the observations should be conveyed at regular intervals. It has also been suggested that one way of maintaining the interest of the observers is to allow them to participate in the preliminary processing and simple analysis of data (e.g. plotting data, computing averages, and noting anomalies).

## Quality Control of Data and Data Processing

One of the main problems connected with the observation of time series is the lack of proper quality control of observed data. This can result from the inability of the observers to make proper measurements due to improper training or to the receipt of inadequate instructions or poor instruments. Lack of interest and therefore motivation, carelessness and, in some isolated cases, even laziness, are cited as factors that contribute to the collection of poor data. Gaps in data series can result from equipment failure, malfunctioning of instruments, illness of the observer, or in the case of special observers, the sudden demand of their primary duties. These gaps are a continuing source of nuisance and frustration, since the data then cannot be adequately analysed by traditional time series analysis. Because the observers do not necessarily have direct communication access to the responsible agency running the programme of observations, remedial action is usually not taken immediately to maintain the continuous observations of the series.

There can be some loss of quality control when different observational and analytical procedures are used by different agencies jointly running the same general programme, for example, at some Ocean Weather Stations in the North Atlantic where a number of nations took part in occupying the same stations, each using a slightly different routine. However, this sort of problem should not be difficult to rectify.

One major factor contributing to the deterioration of data quality is the inability of the responsible agency to analyse the sample and process the data promptly enough. Very few organizations have up-to-date processing capabilities, and it is not uncommon to find an agency that cannot process the data until more than a year later. There have been instances of salinity samples being analysed over a year later (salinity values by this time might be affected by storage in glass sample bottles or by evaporation if they are loosely-capped), nutrient samples being kept in storage beyond their limit of storage, STD/CTP found later to have problems with instrument drift, and calibrations of instruments being changed during the interim. Occasionally the errors in the data are not detected until the final data processing is completed. For example, it may become apparent that a water of unusually high temperature on the sigma-t surfaces might have been due to errors in sampling only after several comparisons have been made with other data.

Because of this delay in data processing, faulty data are not detected in time to take remedial action; nor is it always possible to keep the

observers informed of the analysis results of the data they have observed. Most agencies running the programme have discovered that the collection of data and the subsequent data processing of long, ocean time series data required careful and constant supervision in order to maintain good quality control of data.

## Other Problems

Another problem, though not very serious, involves the addition of extra observations to the on-going, regular programme of time series observations. Requests are made by various agencies and organizations, both within and outside the one which is running the programme, to make observations on their behalf. Usually the requests are reasonable and efforts are made to comply. However, this has the tendency to overload the ongoing programme and results in the draining of the resources of the agency conducting its own observations. In the case of the Canadian weather ship programme most of the requests were complied with, but at the time the additional load contributed to more than 50% of the total work load.

As the time series increase in length and their significance is heightened, there is a tendency for outside sources, both national and international, particularly the latter, to seek the processed data. Usually the purpose of the data use is exactly the same as that planned by the participants of the programme. It is annoying to find the results of the data being published by others when the participants of the programme are so heavily absorbed in observing and processing that they do not have the time to analyse and publish these data themselves. This may be partly due to an internal problem within the organization running the programme but is, nonetheless, an annoyance. One solution to this would be to give the collectors of data ample credit such as including them as co-authors of publications resulting from the use of the data.

Any action at higher levels of administration that enhances the motivation of observers would increase the productivity of good quality time series data. This could be done, for example, by including names of observers, ships, etc. in pamphlets or brochures published by international agencies such as WMO and IOC.

## Lessons that have been learned that would be useful to others

In the foregoing sections dealing with problems encountered in the successful operation of time series observations in the oceans, many of the lessons learned are implicit in the remarks. However, it may be useful to emphasize some aspects of these problems and also to mention others not already discussed, so that persons embarking on a programme of long time series observations will be able to avoid some of the problems encountered in the past.

1. Have reasonable assurance that funding will be maintained. Otherwise, long series would be the first programme to be cut off when money becomes scarce. Without such assurance, the chances are that it would be dropped just when

- the series begins to show some climatic changes of interest. Do not start if this assurance is not given.
2. Attempt to get funding from monitoring studies and surveys under separate budget from research money. Long-time series are difficult to justify because of uncertainty in the results and because one has to wait so long before significant results show up. The programme has to be seen and organized as an integrated system with dedicated and specialized personnel under a manager who is charged with complete overall responsibility.
  3. Ensure that the frequency of observations both in the temporal and spatial scales is adequate to resolve the variability that is sought.
  4. Oversample initially by at least double the frequency originally intended. Reduction in sampling can always be done after enough data have been accumulated to decide what level of reduction would not impair the time series.
  5. Have redundancy in the observational scheme, particularly if automated sampling system is used and the observing site is remote. Gaps in series invariably occur. With redundancy gaps might be patched up. Discontinuous data are difficult to analyse properly by traditional time series analysis.
  6. If shore stations are selected for observation sites choose them very carefully, both in terms of their suitability for scientific purposes and accessibility by observers (e.g. if oceanic conditions are to be monitored avoid sites in proximity of land drainage; if observers have to walk a distance on rainy or windy days to make observations the likelihood of missing data would be greater).
  7. Ensure that there is a dedicated team that can handle a sustained, long series of observations. Select personnel who are particularly patient and careful.
  8. Have only one person responsible for the programme. Having too many inevitably results in conflict and production of poorer-quality data.
  9. It is best to avoid "gadgets" in the team. They are likely to push gadgetry into the programme in preference to data quality.
  10. Avoid changing personnel within the team (assuming that they are good). Some of the technicians staying with the programme eventually get to know so much of the programme and observations that they become indispensable to it. Data quality varies with the observers even when identical instruments are used.
  11. Instructions to observers must be clear and concise. The objectives of the programme and the possible scientific significance of the data should be repeated with every change of observers.
  12. Keep the programme and observations as simple as possible. Sophisticated instruments are capable of measuring more accurately and reliably but their breakdowns are not infrequent, causing unnecessary loss of data.
  13. The problem of sampling cannot be overcome entirely by introduction of automated sampling. New problems frequently develop with the sensitivity of sensors (drift in instruments, corrosion, marine fouling that may affect conductivity readings, etc.). Be certain that adequate precaution is taken to switch over to another method when automated instruments are substituted for non-automated ones. Before the switch is made, however, have two methods of measurements running concurrently so that sufficient data are obtained for intercalibration. Otherwise the homogeneity of the series will not be preserved.
  14. If automatic devices are used, ensure that sufficient calibrations are performed regularly. Drift in the instrument, for example, has resulted in the discarding of several months of continuously-observed data.
  15. If computer-interfaced instrumentation is contemplated, have provisions for hiring an extra electronics-programmer-data processor. Without such assistance one will be left with stacks of data that could remain untouched for a long time.
  16. Never use an unproven instrument for time series observations, especially if measurements are to be made by special observers. When the instrument fails most observers make an honest attempt to repair it, often spending considerable time but without success.
  17. If reliable, sophisticated instruments are available, use them even if they are to be handled by special observers with no experience in using such instruments. To many observers, using such instruments is considered a challenge and they are glad to think that they are contributing to the advancement of science.
  18. Keep data processing up-to-date. Delay in this inevitably results in deterioration of data quality. Also, it will tend to keep the observers motivated because they know that something is being done with the data.
  19. Develop good relations between observers, especially special or "voluntary" observers, and the scientist. Although this liaison aspect of the programme takes a considerable part of the time of a scientist it is worth it as it is one of the ingredients of good-quality data yield.
  20. Listen to the feedback from observers. They may know many operationally-related details that the scientists are not aware of.
  21. Visit the site of the observations more than occasionally. Once every two years seems to be a reasonable frequency.
  22. When liaison involves visits to ships, include ships' agents as well. Make time to talk to the officers and crew of a ship and try to explain why all these measurements are made and why they are necessary. Remember that these observers are the most important link between the data and the scientist. It is essential that only a qualified person goes to the ship.
  23. Disseminate the data to potential users as

rapidly as possible. Feed-back from the users of data may have a significant bearing on the programme -- even support by public-at-large.

24. Unless impractical, use your own ships for time series observations. Ships of other government departments or institutes have other priorities and they usually rate oceanography at the bottom of duty preference. The first programme to suffer is oceanography, with attendant loss of data.
25. Biological observations are seldom taken as time series data. As fluctuations of marine biological resources may be intimately linked to those of physical environment, encouragement should be given to the participation of biologists in any oceanographic time series programme.
26. Initiating a programme is relatively easy. It is the maintenance of the series that is difficult. Once it is started, keep it going!

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