I.O.S.

MEASUREMENT OF CURRENTS IN THE OPEN SEA

BY

W. J. GOULD

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INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey, GU8 5UB.
(0428 - 79 - 4141)

(Director: Professor H. Charnock)

Bidston Observatory,
Birkenhead,
Merseyside, L43 7RA.
(051-653-8633)
(Assistant Director: Dr. D. E. Cartwright)

Crossway,
Taunton,
Somerset, TA1 2DW
(0823-86211)
(Assistant Director: M.J.Tucker)

Marine Scientific Equipment Service
Research Vessel Base,
No. 1 Dock,
Barry,
South Glamorgan, CF6 6UZ
(0446-737451)
(Officer-in-Charge: Dr. L.M.Skinner)

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(This survey was commissioned by the Department of Energy)

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Contents

1. Summary

Techniques of current measurements are reviewed. Failings of existing meters are indicated and desirable developments referred to. The variability of the currents is discussed briefly in the report, particularly as it affects measurement and in more detail in the appendix. Data sources known to the Marine Information and Advisory Service of IOS have been collated to develop an inventory of current observations in the shelf seas around the U.K. and in the N.E. Atlantic.

Conclusions

(1) There are at present severe instrumental problems in the measurement of currents if substantial wave orbital velocities are present. Velocities are likely to be systematically overestimated.

(2) The geographical coverage of current observations is poor in the shallow seas generally and worse in open ocean. Few 1° squares have any measurements at all. The situation is even poorer when it is noted that at the majority of places only a month or two's data are available.

(3) Consequent on conclusions 1 and 2 the availability of good data in the important near surface zone is very poor.

(4) It is possible that proprietary data from companies would augment the data substantially but we have no knowledge of its quality.

Recommendations

(1) For future measurements of currents to be of maximum value potential users should define their requirements for data products and accuracy. Most current measurements now available were made in the course of scientific

research programmes. They are not necessarily in the form most suited to meet other users' requirements.

(2) Programmes of measurement should be continued and extended. Present understanding of open ocean circulation suggests that observations at each locality extending over 2-3 years may be needed for a description of the variability of the currents there.

(3) In shallow water extended geographical coverage is required to adequately describe variability due to variations in the bottom depth. Such detailed description is needed to improve the value and relevance of numerical models.

(4) The development of new sensors for the measurement of currents should be supported where they show promise of eliminating the faults of existing instrumentation particularly in the near surface wave zone.

(5) At the same time a study should be made of the dynamics of surface and subsurface moorings to determine the best platforms for the deployment of the new sensors.

(6) Consideration should be given to supporting a development programme for remote (autonomous) acoustic tracking stations moored in deep water in the N.E. Atlantic to track freely drifting floats at a variety of depths for less periods of time.

2. Introduction

Currents in the open sea are complex. They are driven by wind stress at the sea surface, by solar heating and by the tide raising forces of the sun and the moon. They are affected by continental boundaries, bottom topography and the distribution of density within the water column.

On a global scale these forces establish a pattern of average ocean circulation having such strong surface features as western boundary currents (typified by the Gulf Stream) and flows between one ocean basin and another. Superimposed upon the mean pattern are fluctuations attributable to oscillations in the driving forces or to instabilities in the mean circulation. They are present on a wide range of depth and time scales and present severe problems of measurement and interpretation. Away from the strong boundary currents these fluctuations appear to be the dominant feature of the deep ocean circulation.

This report discusses the problems associated with the measurement of currents in the sea and makes recommendations on how they may be overcome. The report is divided into three sections which deal with

(a) the nature of currents in the ocean; in particular the way they vary with time and the problems that this variability introduces in their measurement,

(b) the ways in which currents can be measured, the general limitations of various types of measurement system in relation to the variability of the ocean and the steps that should be taken to overcome them,

(c) an assessment of the quantity and quality of the measurements that have been made around the British Isles.

The main sections are supplemented by an extensive appendix, with references, which gives a more technical background to the subject matter of sections 3 and 4. It is assumed that a primary purpose of the report is to emphasise factors in the measurement of currents that are of particular relevance to offshore engineering activities such as the deployment of offshore structures and the operation of submersibles. It should be stressed, however, that decisions on the types of data required, especially in deeper water, depend on engineering criteria beyond the scope of this report.

These decisions must be taken soon if timely programmes are to be put in hand.

3. The nature of currents in the open ocean

In all areas of the open ocean the long term mean circulation has superimposed on it oscillations over a wide range of frequencies and horizontal and vertical spatial scales. These oscillations are of great importance since in general they make up the most energetic components of all currents measured in the deep ocean and in continental shelf seas.

In most areas around the United Kingdom the mean flow, taken over a period of several years, though of interest in the study of the transport of pollutants and their dispersal, is probably not of great practical importance to the safety of structures. Nevertheless the few areas of high mean currents need to be clearly defined. It is known for example that in the vicinity of the Faeroe Bank Channel and locally in the northern Rockall trough rather steady currents approaching 100 cm/sec exist.

An account of the principal factors contributing to the time dependence of the currents is given in the appendix. In the following table those features most likely to produce significant velocity fluctuations are summarised.

Oscillations of direct interest in the design of offshore structures

Type of oscillation	Typical speed of water motion cm/sec	Typical period	Geographic areas	Vertical extent
Mesoscale eddies	5-100	30-100 days	All deep oceans	Throughout depth
Inertial oscillations	5- 50	0.5-5 days	All seas and oceans	Throughout depth
Tidal oscillations	10-200	0.5-1 day	All seas and oceans most energetic on shelf	Throughout depth
Meteorologically forced motions	Up to 100	0.5-5 days	All oceans and seas	Top 100 m
Surface waves	Up to 200	1-20 secs	All oceans and seas	Top 30 m

The inertial currents arise as the free response of the ocean to an impulsive force. The mesoscale eddies with horizontal dimensions of several hundred kilometres are a dominant feature of the currents of the interior of the deep ocean. Their advection past a fixed point leads to apparent oscillatory periods of 30-100 days. They may be likened to atmospheric depressions and anticyclones but with different length and time scales.

The presence of surface waves of the higher frequencies will be seen to lead to problems in the measurement of the lower frequency currents. Apart from these problems the main requirement to be satisfied from any system of measurement is that the recordings should be taken for a sufficient length of time to ensure that an adequate description of the oscillations is obtained. The frequency of sampling should also be sufficiently high for the oscillations to be adequately resolved.

Currents on the continental shelf

Existing records in the shelf seas typically approach the one month's duration sufficient both for a good determination of tidal components and to learn something of the causes of the other less deterministic higher frequency currents. However the achievement of adequate statistics of even these currents requires many months of data since as yet there is no precise physical understanding of all the processes involved in their generation.

Clearly the whole of the continental shelf seas cannot be covered by a closely-spaced grid of observing sites and numerical models have a role to play in understanding how the known current characteristics at one site may be extrapolated to give reliable information at nearby positions, even though the limitations referred to above in our knowledge of the forces generating the current (such as the wind stress) may prove a major restriction on the accuracy of such models.

Currents in the deep ocean

The substantial technical difficulties involved in making adequate current measurements in deep water are discussed in the next section. Astronomical tides are less strong and comparable in strength with inertial oscillations which, except at very low latitudes, are of similar period although arising from quite different causes. Additionally lower frequency motions with durations of several months can assume a dominant role. This means that measuring programmes at particular sites must be maintained over periods of between 2 and 5 years in order to gain adequate information about the energetics of these long period motions. The existence of such motions has been demonstrated in many parts of the oceans of the world but much work remains to be done to understand the distribution in space and time in any particular area.

Moreover both tidal and inertial currents have a complex vertical variation with depth which may be studied either through the deployment of many current meters on a mooring or by the use of profiling instruments. The former technique would require the commitment of a very substantial proportion of the U.K. stocks of current meters held in scientific institutions (100 current meters). No equipment at present exists in the U.K. to make vertical velocity profiles with sufficient vertical resolution to make a study of the vertical distribution of inertial energy in the deep ocean.

4. Methods of current measurement at present in use

Current measuring techniques may be subdivided into two basic categories, using

(a) current meters-involving the measurement of a time series of velocity vectors at a fixed point,

(b) drifters-where a marker is used to track the motion of a parcel of water.

There are in addition a few other techniques such as current profiling and some indirect measurement techniques which do not clearly belong to either major class.

(a) Current meters

We shall confine ourselves to a discussion of recording current meters which can be placed, unattended, in the ocean to record their data internally. The main development of such instruments has taken place within the past decade and there are now commercially available a variety of recording current meters of which the majority are well engineered and reliable.

The majority of such instruments record current speed by counting the revolution rate of a Savonius rotor or a propeller and sense the direction of current flow by measuring the orientation of a vane relative to the local magnetic meridian.

With a very few exceptions the current speed is recorded as a scalar mean typically over a 10 minute sample period and this is associated with a pair of direction values measured at the beginning and end of the speed sampling period. We shall classify these instruments as having a simple sampling scheme. These instruments clearly can give no information about motions with periods shorter than the sample period. The choice of sample interval is at present a compromise between the need to resolve the highest frequencies contributing significantly to the record and the ability of the instrument to store the data.

An alternative sampling scheme is to record values of current speed and current direction at a much more frequent rate (say 1 per second) but for only one minute in every ten. This gives information about the higher frequencies but means that long records can be still obtained (this technique is called burst sampling). The most complex current meters using rotors and vanes sample the direction 8 times during each revolution of the rotor and use an internal computer to produce a vector average current over a sampling period of a few minutes. Such instruments then adequately sample motions with periods of a few seconds (these are known as vector averaging current meters VACM). They do not however record information on surface wave frequency motions.

The majority of these recording instruments have a data storage capacity (on magnetic tape) of the order of 10,000 samples, equivalent for instance to one sample every ten minutes for about 60 days.

All of these instruments when properly maintained, set and recovered have given data returns of the order of 80-90%.

Deployment of current meters in the deep ocean

For measurements below the top 200 m of the water column it is most usual to deploy the current meters from moorings with subsurface buoyancy. This may be entirely at the uppermost end of the buoy line or distributed throughout the mooring - the latter approach permits designs of moorings which return part of the mooring to the sea surface in the event of the mooring breaking. Recovery of the buoy is by means of an acoustic release which on receiving an acoustic command from the recovery ship separates the buoyancy and instrumentation above the release from the anchor below allowing the buoyancy to return to the surface. Such moorings have been successfully deployed by I.O.S. for durations of up to 6 months.

In cases where measurements have to be made very near the sea surface a simple mooring with a surface following toroidal buoy is used - there are grave disadvantages to the use of such a design and this problem will be dealt with later.

Deployments in shallow water

The most commonly used mooring type in shelf seas (known as the U-mooring) has the current meters on a mooring line with subsurface buoyancy. This is connected via a ground line of length typically twice the water depth to another buoy line attached to a surface toroidal buoy. In this way the subsurface buoy can be recovered without the use of an acoustic release and if the surface buoy is lost or damaged recovery can be attempted by dragging for the ground line.

Simple single point moorings similar to those used in deep water can also be used. The relative shortness of the mooring line in shallow water enables much heavier wire to be used than is the case in deep water. A serious hazard to moorings in shelf seas lies in trawling activity in their vicinity. A high proportion of all lost or damaged moorings can be attributed to this cause.

U-moorings have usually been deployed for periods of 60 days or less.

Measurement of currents in the presence of surface wave frequency motions

It is assumed here that the most important data needed for engineering studies is a resultant of low frequency currents and those due to surface wave motions.

Motions at surface wave frequencies are recorded by current meters

(a) deployed within the near surface depth range in which the wave orbital velocities are significant,

(b) on moorings with surface buoyancy where the surface wave motions are transmitted down the buoy line,

(c) on moorings with subsurface buoyancy which is affected by wave orbital motions.

These problems are not confined to the upper layers of the ocean since for a surface mooring, although horizontal movements of the mooring line due to the motion of the surface buoy are rapidly damped with increasing depth, vertical motions at surface wave frequencies are transmitted down the mooring line with very little attenuation. These motions have been shown to sometimes overestimate the currents by 100% at depths as great as 2000 m.

The influence of surface wave frequency motions has been shown to have the following effects in the measurement of lower frequency motions.

(a) All conventional (rotor/propeller and vane) current meters over-read on surface moorings in deep water.

(b) Current meters with rotors and simple sampling schemes over-read in shallow water on surface and subsurface moorings. On subsurface moorings the degree of over-reading is dependent on the depth of the buoyancy below the surface.

(c) In deep water there is good agreement between VACMs and free drifting drogues in the uppermost layers (10 m).

A considerable body of information on the intercomparison of various current meters in differing conditions has been accumulated. The vast majority of it points to the fact that all conventional (rotor/propeller and vane) current meters are incapable of giving a true representation of ocean currents when they are affected by motion at surface wave frequencies. The magnitude of the effect can be very large (to the extent that measured currents may be 300% of the true values). The only data unlikely to be affected are those collected on subsurface moorings, provided the uppermost extension of the instrumented buoy line is below the influence of the surface wave orbital velocity (which may be as deep as 100 m). Information on mooring design and on prevailing wave conditions may be a useful indication of the reliability of current measurements but is not adequate to correct spuriously high readings. If the waves are superimposed on a low frequency current strong enough to prevent flow reversal the errors will not be as great.

The next generation of current meters

The problems outlined above are attributable in the main to the inability of the direction sensor to align properly with the flow at surface wave frequencies. Lags in response of rotors or propellers to speed changes may also contribute. It is difficult to match the response of the speed and direction sensors over a wide range of current speeds.

A probable solution lies with the use of sensors which measure directly the orthogonal velocity components with identical sensors with sufficient high frequency response to adequately define motions with periods of a few seconds. Such sensors have been developed, the most promising are electromagnetic and acoustic devices, but they are not as yet available in forms which would enable them to be used as replacements for the recording current meters now commonly in use. The further development of such instruments appears essential if reliable current measurements are to be available from the upper layers of the deep ocean or shallow seas.

(b) Lagrangian current measurements

In Lagrangian methods the determination of the position of the marker, whether it be a drifting buoy at the surface, a neutrally buoyant float or parachute drogue, is the observation that is made. The method is excellent for exploratory work over a region and is complementary to the mooring measurements. Freedom from noise arising from mooring motion or from instrumental imperfections enhances the potential accuracy of the measurements although errors arising from the inertia of the marker in an accelerating flow will remain. In addition the use of remote tracking techniques can make such measurements without the need for long periods of ship involvement.

The simplest techniques that have been used have been by the deployment of large numbers of sea surface or sea bed drifters or drift cards. These when found are returned by the public and a reward given. Only the release and recovery positions are known together with the elapsed time between the two events. Thus only the most rudimentary information on circulation patterns is produced and this is subject to uncertainties in the behaviour of the drifters between launch and retrieval. The method has been used in investigations of oil pollution.

Another commonly used technique is that of tracking a surface buoy attached to a drogue at the depth at which measurements are to be made. The tracking may be achieved from shore based stations either via radio navigational aids such as Decca, Loran or Omega or on a world wide basis using the tracking capability of the NIMBUS satellite. This latter method has been used to track buoys in deep water west of the U.K. and in may other parts of the deep ocean. Tracks several hundred days in length have been achieved. The inherent disadvantage of any drogue method is the difficulty of estimating the slippage of the drogue relative to the water although this may only be a few cm/sec. It arises from a current shear between the drogue and surface marker or through the wind drag on the latter.

These errors are largely removed by the use of neutrally buoyant floats which are designed to be less compressible than sea-water. This development, first made by the N.I.O., has been used predominantly in the deep ocean. The float is accurately ballasted to sink from the surface until the effect of the differential compressibility of the float and water allow it to settle at some predetermined pressure level in the ocean and drift around with the water movements at that level. The float is tracked acoustically. A system developed in 1972-3 at I.O.S. is capable to tracking up to 20 floats anywhere in the deep ocean and at any depth and has achieved acoustic ranges of up to 80 km. The tracking is performed by an attendant ship.

The most promising development in this field has been the use of shore based acoustic listening stations in the Caribbean to track the motion of neutrally buoyant floats at depths near the minimum in the sound velocity profile (the SOFAR Channel, ca. 1200 m). Floats have been tracked at ranges in excess of 1000 km and over periods in some cases in excess of 3 years.

Such a system is very economical in ship time (ships are only needed for deployment and recovery of floats), can cover a large area of ocean (the area at present covered by 4 stations in the western N. Atlantic is equal to one bounded by 50° to 60°N and from the continental slope of Western Europe out to the mid Atlantic ridge. Under certain conditions the technique has been extended to cover the part of the water column from 500 to 2000 m.

The technique is particularly powerful in demonstrating whether there are substantial mesoscale eddies present and whether the bottom topography is playing an important role in modifying the flow.

Autonomous listening stations could be developed which could be placed in any ocean area and the use of these could make SOFAR float tracking feasible in any area of interest. The implementation of such a Lagrangian current monitoring scheme could provide a great amount of information on areas of the N.E. Atlantic which hitherto have not been studied using moored buoy techniques, and could serve to delineate the areas in which the most energetic motions are likely to be encountered.

5. Current data from the U.K. continental shelf and E.N. Atlantic

A review has been made of published and unpublished data inventories from U.K. scientific establishments. The data include only measurements made from moored buoys up to mid 1975 but these comprise the vast majority of current measurements in the area under consideration.

A direct outcome of the review is a combined inventory of the current meter data.

The geographical distribution of current measurements is shown in fig. 1. The number in each 1° square is the number of hundreds of current meter days of data, e.g. 7 represents between 700 and 799 days of data, 0 represents less than 100 current meter days. No distinction is made between data from a single current meter for 100 days or 10 current meters simultaneously for 10 days or 100 current meter days of data collected at irregular intervals over a period of years. The spatial distribution is extremely non uniform with many areas of the continental shelf and deep ocean devoid of measurements. The most intensively studied areas are the southern North Sea and the Irish Sea together with a few isolated areas of the deep ocean in which specific scientific studies have been carried out. In only eight squares does the total number of current meter days exceed 1000 (about equivalent to 3 years of record). Three of these areas are in the North Sea, two north of Scotland, one in the Irish Sea, one in the Celtic Sea and the eighth is on the continental slope in the South West Approaches.

It is clear that with so few very long measurements there is little opportunity of selecting suitable periods for the study of meteorologically forced motions in shallow water nor of mesoscale activity in the deep ocean.

Fig. 2 shows the number of individual months between 1967 and 1975 in which there have been current measurements in specific 1° squares. The presentation clearly shows the lack of continuity of measurement at the majority of sites. Many of the areas, which in figure 1 appear to have many current measurements, are seen to have received intensive study for only brief periods.

The length of individual records in deep ($>$500 m) and shallow ($<$500 m) water show a rather different distribution (Fig. 3). The majority of shallow water records are less than 20 days long, a figure probably governed by the hazard to longer measurements presented by trawling. The longest individual shallow water records are 70-80 days.

In deep water more than half of all records are 30 days or less in length and the longest without replacement are between 120-130 days. Subsurface deep water moorings are capable of deployment for periods of up to 9 months, but the data capacity of the presently available instruments would only permit readings to be obtained once per hour over that period.

The durations of individual records above show that many can be used to study tidal and inertial oscillations and other motions at higher frequencies. The study of much lower frequency processes requires the "patching" together of many such records to obtain a long time series.

The difficulty in making measurements near the sea surface is reflected in the percentage of records which were taken within the depth ranges specified below. Only 5% of all records in shallow water were collected from the uppermost 10 m of the water column.

In shallow water current meters at less than 10 m are directly affected by wave orbital motions which if large enough to cause flow reversal will seriously affect the majority of existing current meters.

In contrast to the near surface situation there is a larger body of data from near the sea bed which can be used to study sediment movements and sea bed erosion and scour. (37% of all shallow water records are from the bottom 10 m of the water column).

6. Appendix

Ocean current variability

Table A1 expands an earlier table. Particular processes are often concentrated in frequency bands as illustrated by the spectrum in fig. A1* but the coexistence of these processes serves to increase the difficulties of making accurate measurements of currents in the deep ocean and in shelf seas.

The physics of many of the motions is as yet not well known and research is at present being undertaken to investigate the generation mechanisms and geographical distribution of the motions. Examples of the evidence for and the nature of the various types of motion are included in the references and in the following summaries.

Mean flows, in this context currents averaged over a period of several years, are in much of the ocean believed to be weak (a few cm/sec) but can in places exceed 100-200 cm/sec. Areas with higher probability of strong mean flows are

(a) submarine boundaries between oceans. The Faeroe Bank channel between the Norwegian Sea and Atlantic has currents over 100 cm/sec in it as does the Straits of Gibraltar,

(b) western ocean boundaries. The Florida Current and Gulf Stream are typical of currents in such regions,

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*This figure is taken from Webster (1967) and is a composite of two spectra. Below 1 cph the record is from a depth of 98 m on a mooring with subsurface buoyancy and is thus relatively free of surface wave effects; at frequencies above 1 cph the record is from a depth of 50 m on a surface buoy mooring. Both records were taken in a water depth of 2600 m at 39°20'N 70°00'W using a Richardson-type current meter (Richardson, Stimson & Wilkins, 1963). The plot is scaled in units of the square of the velocity so that the height of the spectral peak gives a representation of the energy of the motions at that frequency.

(c) equatorial currents - not well understood as yet but included here as examples of substantial currents which remained undiscovered until little over a decade ago.

Climatic change is beyond the scope of this paper, undoubtedly the general circulation of the oceans has altered due to major climatic changes such as ice ages. Shorter period climatic change has been associated with changes in oceanic conditions. Dickson & Lee (1969) demonstrate a strong correlation between atmospheric circulation patterns and variability in oceanographic conditions (temperature and salinity) in the surface layers of the N. Atlantic and of the shelf seas around the coasts of the U.K. It is reasonable to assume that associated with these oceanographic changes there are changes in ocean currents. Due to their long period such changes are impossible to detect in the direct instrumental current measurements that have been made up to the present time.

The seasonal variability in the pattern of surface temperature and salinity of the oceans is quite well known and is associated with seasonal cycles of precipitation, insolation and wind stress. The variability is in general confined to the upper layers of the ocean above the main thermocline (where it exists). Examples of such variations are given by Schroeder & Stommel (1969) and by Middtun (1969). As in the case of climatic change the seasonal effects on circulation patterns are for the most part small and hence not detectable in the relatively short records of currents at present available. A notable exception to this is the case of the Somali current in which dramatic seasonal changes are related to the onset of the Indian Ocean Monsoon (Leetmaa, 1972). It appears also that the currents flowing across ridges between ocean basins can be significantly affected by seasonal changes in atmospheric pressure gradients.

Mesoscale activity in the oceans may be likened to the existence of cyclones and anticyclones in the atmosphere but with time scales of weeks rather than days and space scales of hundreds rather than thousands of kilometres. There is reason to believe that variability associated with these mid-ocean eddies is present in all the major ocean basins of the world (Swallow, 1976). Evidence for the existence of oceanic structures on scales of a few hundreds of kilometres from direct current measurements was demonstrated in 1959-1960 (Crease, 1962) followed by the Soviet POLYGON experiments (Brekhovskikh, Fedorov, Fomin, Koshlyakov and Yampolsky, 1971; Fofonoff, 1976) and the joint U.S./U.K. Mid-Ocean Dynamics Experiment (MODE-1) (MODE-1 Scientific Council, 1973), (Wunsch, 1976), (Freeland & Gould, 1976a,b) in which a variety of direct current measurement techniques were employed (Gould, 1976).

The observations in these experiments revealed features in the low frequency circulation with velocities as high as 50 cm/sec in the upper layers of the ocean and with a horizontal diameter of between 100 and 140 km. The current vectors at deeper levels revealed a more complex eddy structure with a reduced current amplitude. By filtering out the higher frequency motions maps have been produced of the low frequency flow field (Freeland & Gould, 1976b), fig. A2, and syntheses made of the structure of the currents (McWilliams & Flierl, 1974).

In enclosed or semi-enclosed shelf seas the passage of meteorological disturbances can result in the production of appreciable aperiodic flows. These flows when constrained by lateral boundaries cause appreciable surface elevations or depressions (storm surges). There are several well documented examples of direct observations of such meteorologically forced flows (Howarth, 1975; Dooley, 1971; Caston, 1976) and much work is being carried out on the numerical (Heaps, 1974) and analogue (Ishiguro, 1972) modelling of such forced motions. The flow velocities associated with the surges may be large. In the case of Howarth's measurements in the Southern Irish Sea the meteorologically induced velocity was as high as 50 cm/sec.

The passage of meteorological disturbances may also initiate shelf and edge waves in seas and oceans of variable depth. Such oscillations are trapped along depth discontinuities and propagate parallel to the depth contours. Theoretical studies of such motions have been made primarily by Rhines (1969), Buchwald & Adams (1968), Buchwald (1973), Smith & Cutchin (1973) and more recently by Huthnance (1975) and Allen (1975).

Another class of meteorologically induced motions is that of inertial oscillations. These have been observed both near surface and at depth and both on and off the continental shelf. The motions have a period of $12/\sin\lambda$ hours where λ is the latitude. This gives values of 12 hours at the poles, 24 hours at 30° North or South andinfinity at the equator. The value in the area of Rockall for instance is 14 hours. A survey of these motions was made by Webster (1968) and owing to the great increase in the number of current measurements made since that date there are many more recent observations available (Gonella, 1971; Perkins, 1972). The initial observations of time series at fixed levels revealed low vertical coherences (Webster, 1972; Siedler, 1972). The implication that this implied short wavelengths in the vertical direction is confirmed by vertical profiling techniques (Leaman & Sanford, 1975) in which wavelengths of typically 100 m were observed. This complex structure results in a burst-like characteristic signature of inertial oscillations in a time series record (fig. A3).

(Fig. A3 shows three commonly used means of displaying current time series. (A) is known as a progressive vector diagram and is formed by continuously adding the measured velocity vectors and plotting the hypothetical path of a water particle. It should not be confused with a true particle trajectory because the particle always senses the flow vector at its present position whereas the progressive vector diagram is made up of flow vectors from a fixed point. (B) is a kinetic energy spectrum showing the distribution of the energy in the record between various frequency bands. (C) is produced by a process called complex demodulation and shows the amount of energy in the record at a particular frequency as a function of time).

Tidal oscillations in the shelf seas are often the dominant motion. In the waters around the U.K. the tides are, except in a few special cases, semi-diurnal (fig. A4) and thus have a frequency close to the local inertial frequency. In stratified conditions both on the shelf and in deep water the tidal current may be resolved into a barotropic component (uniform over the entire depth) and a baroclinic component varying with depth. In general the barotropic component is directly related to the astronomical forcing and is thus predictable from a single set of observations in an area.

The baroclinic (or internal tide) is not predictable since it is affected by stratification and topography. Studies of observations of tidal currents have been reported by Cartwright (1969), Huthnance (1973), Huthnance (1974), Gould & McKee (1973) and a review of all work on baroclinic tides is given by Wunsch (1975).

Freely propagating internal waves (waves sustained by density stratification in the ocean) are found in the range of periods from the inertial (typically 14 hours) to the local Brunt-Vaisala stability period (related to the density gradient in the water and varying from minutes to hours) (Briscoe, 1975a). The relative importance of this band of frequencies in comparison to the tidal and inertial peaks in one geographical area may be assessed by reference to fig. A1. The kinetic energy density falls off with a power law close to $(\text{frequency})^{-2}$ (Garrett & Munk, 1972). The spatial and temporal structure of internal waves in the deep ocean has been the subject of many investigations culminating in the IWEX experiment (Briscoe, 1975b).

The great importance of surface wave frequencies is clear from the data of figure A1. In general, measurements of currents are made with a sampling interval of between a few minutes and an hour. Velocity fluctuations at higher frequencies are thus misrepresented (aliassed). The fact that surface wave motions can be so energetic has serious implications for the measurement of lower frequency currents in the deep ocean and in shelf seas and clearly also in the design of surface piercing structures.

Instabilities of surface and internal waves, the latter dependent on both shear and density gradient, can lead to intense patches of turbulence which may be responsible for substantial mixing in the ocean.

Shortcomings of current meters in the presence of surface wave frequency oscillations

Webster (1967) presented the need for caution in the design of sampling schemes for current meters. He pointed out that the high energy at surface wave frequencies could produce severe aliassing problems in instruments which typically sampled current velocity only once every few minutes.

In spite of these early warnings many current meters presently in use do not sample currents in such a way as to adequately monitor or eliminate surface wave frequencies and such instruments when used in the presence of wave energy can produce spurious current records.

An experiment conducted under the auspices of SCOR Working Group 21 in 1970 brought to light systematic differences between current meter records taken on surface moorings by instruments which employed the suggested sampling scheme of Webster (1967) and those which did not. These differences which were large were attributed to the different responses of the current sensor (Savonius rotor) and vane of the current meters used. Conclusion 4 of that report states:- The records from Bergen (Aanderaa), Braincon and Plessey instruments showed a striking absence of low speeds, due to the presence of appreciable energy at frequencies too high to be resolved by the sampling regimes of those instruments.

The subject of data sampling schemes has been studied further by Gould (1972) who in tank tests showed that an Aanderaa instrument when subjected to transverse oscillations of periods in the range of 10-40 secs recorded rotor revolution rates which even when corrected by the cosine of the angles taken up by the vane over-read by as much as 179%.

These tests suggested that current meters which employed omnidirectional Savonius rotor speed sensors, large vanes and rather sparse sampling schemes would, in the presence of surface wave frequencies, give current records which significantly overestimated the current magnitude.

A further study by Gould & Sambuco (1974) demonstrated that these differences were present in records of current meters not only close to the sea surface but throughout the water column when the moorings on which the instruments were installed had surface following buoys. This finding was further confirmed by another SCOR WG 21 current meter intercomparison.

At the time of these experiments a new current meter employing a much more complex sampling scheme was developed. If the problem of over-reading in the presence of surface waves was solely one of aliassing (a sampling problem) then it followed that a much more rapid sampling scheme together with a vector averaging capability might overcome the problem. The vector averaging current meter (VACM) was developed from the Geodyne (Webster sampling scheme) instrument. The current meter employed the same sensors, Savonius rotor and vane, but the current direction was sampled once for every $\frac{1}{8}$ rotor revolution and the directions were then resolved into east and north components and summed by an internal computer. The resulting vector averages of east and north components were recorded internally every 15 minutes.

In order to assess the adequacy of this improved sampling scheme the new VACM and the old Geodyne were deployed at common levels on two nearby moorings - one with surface buoyancy, the other a subsurface buoy. The results of this intercomparison showed that both instruments recorded higher speeds on the surface mooring than on the subsurface demonstrating that the shortcoming was not solely one of sampling regime. This result was true at depths of 200 and 1000 m in 2000 m of water and illustrated that vertical motions at surface wave frequencies were transmitted down the surface mooring line to great depths (fig. A5). The problem then was one of sensor response rather than sampling and it was seen that adequate sampling was a necessary but not sufficient condition for the collection of realistic records in the presence of surface wave period motions.

At present several alternative velocity sensors exist but as yet only in the development stage. Prototype instruments using both electromagnetic and acoustic orthogonal velocity sensors have been used in the ocean and appear to have overcome the problems of the previous generation of instruments in the wave environment. Figure A6 shows a comparison between records from a vector averaging current meter (VACM) and an acoustic current meter at a depth of 35 m beneath a spar buoy. The records illustrate the over-reading of the rotor/vane VACM due to the inability of its sensors to respond to the wave frequency motions (Saunders, 1976a). A further comparison by Saunders (1976b) of freely floating drogues and VACMs under a surface following toroidal buoy shows much better agreement which is attributable to the higher mean flow velocities.

The preceding remarks refer to experiments conducted in water of considerable depth (2000 m or more) and may not necessarily be valid for measurements in shelf seas. In shallow water the scope for motions of the mooring line under a surface buoy is much less than in deep water and typically the low frequency currents to be measured are much more energetic (perhaps 50 cm/sec rather than 5 cm/sec). Thus it might be expected that current meters with adequate sampling schemes and small sensors might behave adequately in a wave field on the continental shelf except at slack water.

An experiment by Halpern (1974) in which data were compared on surface and subsurface moorings in water of 100 m depth suggested that in this situation all the current meters used (VACM and Geodyne on surface buoy and Aanderaa on subsurface buoy) gave the same results to a high degree of accuracy (Fig. A7). Discrepancies did occur but only at high frequencies (0.45 cph).

There is further possible source of error in the measurement of low frequency currents in the presence of strong tidal and inertial signals. The hodograph of such motions may typically be a straight line through the mean velocity coordinate or an ellipse centred on that position. Such strong reversing flows may introduce errors into the computed mean currents if there are systematic non-linearities in the direction sensor. If the direction values are higher than true on one half of the tidal cycle and lower than true on the other half cycle then the vector mean computed over the complete cycle will show a spurious residual. Gould (1973) made a study of this and concluded that the error amounted to typically 1% of the tidal/inertial amplitude for every 1° of non-linearity. Thus a 10° non-linearity in the presence of a 50 cm/sec tidal signal would produce a spurious 5 cm/sec mean flow. In the presence of weak mean flows such an error could entirely reverse the apparent mean flow direction.

If care is taken with direction calibrations and these calibrations are applied in the data processing such problems may be avoided.

Summary

The present state of knowledge suggests that rotor/vane current meters are inadequate in their ability to accurately measure low frequency, low amplitude (20 cm/sec) currents in the presence of vertical motions at surface wave frequency. However current meters which adequately sample the high frequency motions of the speed and direction sensors and in which the sensors are also capable of adequate response are capable of making meaningful measurements in the presence of horizontal wave orbital motions. If isolated from these high frequency motions all properly calibrated current meters whether employing simple or sophisticated sampling schemes are capable of adequately representing low frequency currents to within the calibration reproduceability (1-2 cm/sec).

Mooring types

In view of the foregoing remarks regarding the effect on current meters of the type of mooring used in their deployment some attention should be given to the types of mooring commonly in use in shelf seas and deep oceans and to their relative advantages and disadvantages.

As has been stated before there are two basic types:

(a) those employing subsurface buoyancy,

(b) those with a surface marker.

Fig. A8 shows typical layouts of these moorings in addition to a composite U-shaped mooring commonly used in continental shelf areas.

Type 1 is a deep-water surface mooring which commonly uses for buoyancy a 6 or 8' diameter toroidal buoy and a half to one ton clump of scrap iron as anchor. The scope of the mooring is small and often less than the water depth. Such a design is made possible by the inclusion of nylon or terylene sections in the deeper parts of the buoy line. In the upper part of the mooring 6 to 8 mm torque balanced wire is typically used as fibre ropes are susceptible to fish bite in this depth range. Instruments are placed anywhere in the mooring line. The disadvantage of this simple configuration is that the entire mooring line is subjected to vertical surface wave frequency motions which are transmitted virtually undamped down the buoy line (fig. A5) and thus are capable of contaminating current records at any level. Recovery of the mooring can be eased by putting a time or command release immediately above the anchor. The surface buoy can be instrumented to make meteorological observations and instruments can be placed in the uppermost layers of the ocean.

Type 2 is of similar construction to type 1 except that the buoyancy is below the sea surface. Typical buoyancy used for such a mooring might be a spun steel sphere giving a lift of the order of 1500 lbs. Here the use of synthetic line in the lower part of the mooring has the advantage of reducing the total weight of the line and thus in increasing the stiffness of the mooring. Large buoyancy modules such as steel spheres have limited depth capability and are typically restricted to depths of less than 500 m. This means that the upper part of the mooring line is subjected to the relatively high currents found in the upper layers. Such currents deflect the mooring from its vertical mean position and prevent instruments from being kept at a constant depth. In strong currents the depression of a point near the top of such a mooring could amount to several hundred metres in depths of several thousand. The mooring is recovered by the inclusion of a release unit above the anchor. This mooring is free from surface wave motions.

Type 3 is a variation of 2 but with buoyancy distributed along the mooring line. Glass spheres in protective plastic cases are at present the most cost effective deep buoyancy available. This technique can be used to improve the stiffness of the type 2 mooring since buoyancy can be put in the deeper part of the mooring, where currents, and thus drag, are much less. By suitable design and inclusion of deep buoyancy in subsurface and surface moorings the recovery of instruments may be ensured even in the event of a breakage of the mooring line since residual buoyancy remains which is sufficient to bring the remaining mooring components back to the surface when the anchor is released.

Moorings in shallow water are extremely vulnerable to such activities as trawling, mineral recovery, interference by pleasure and commercial craft.

Type 5 is a simple subsurface buoy with ground line (a release unit could also be used). In the very high currents experienced in shelf seas the drag on the mooring line may cause large depressions of the upper end of the mooring and large mooring line angles.

The most commonly used mooring in U.K. continental shelf areas is the U-mooring, type 4, a composite subsurface mooring line on which instruments are inserted together with a ground line and surface marker (Baxter, 1975; Howarth, 1975). Such a mooring has the advantage of not requiring acoustic command release equipment, of having a main mooring line isolated from surface wave motions and of having the possibility of making meteorological measurements from the surface buoy.

Lagrangian techniques

The tracing of the path of a parcel of water may be performed in a variety of ways but each falls short of the ideal and has some limitations.

Within this group we shall consider the following techniques:

(1) The tracking of drogues attached to surface marker buoys. These may be tracked:-

   (a) by visual observation,
   (b) by retransmission of radio-navigational aids,
   (c) by satellite.

(2) The use of neutrally buoyant floats.

Drogues may be set at any depth and attached by thin wire to surface markers. The fact that the observation of current is not free of influences from other depths and from the sea surface introduces errors due to shear in the water column and to the wind drag on whatever surface marker is used. This is one of the inherent sources of inaccuracy in such a method. Such drogues do represent a possible method of measuring currents in the near surface layer of the ocean (where the length of wire connecting drogue to surface marker is minimised) but the problem of wind drag and, in the very shallowest depths, interaction of the drogue with wave orbital velocities makes the technique of limited usefulness for measurements of high accuracy. Studies of the dynamic response of drogues may be expected to improve the value of the technique. Little has yet been done on this aspect of the problem.

The methods of tracking drogues vary from the simplest visual observations or to satellite tracking procedures.

The former is obviously limited in the range of ocean which can be covered (within line of sight of a ship or land) and the accuracy with which velocities may be determined are of course dependent on the accuracy of fixing and interval between observations.

The limitations may be relaxed by employing radio-navigational aids such as Decca, Loran or Omega (Phipps et al., 1975). A tracking technique is used in which the radio-navigation signals are retransmitted from the buoy and interpreted at a shore based station to provide a fix on the drogue. The tracking may then be continuous but is still capable of use only within the range of availability of these navigational systems.

This restriction disappears if use is made of the Nimbus-6 satellite system which enables a surface marker (attached to a drogue) to be located anywhere within the world to within about 2 km. The system is capable of transmitting other environmental data back to a shore based station.

Given constant positioning errors all Lagrangian measurements increase in precision as the time between position fixes increases. They are thus not suitable to assess the maximum velocities likely to be encountered over short periods of time.

The use of neutrally buoyant floats which are tracked acoustically is a technique in which no attachment to the sea surface is necessary. The floats may be ballasted to float at some preset pressure level to within ±50 m. This, except in strongly stratified shelf seas, makes their use in shallow water difficult as also does the more difficult shallow water acoustic conditions. Neutrally buoyant floats have, in their most recent form, been used successfully to define horizontal spatial flow patterns over periods of days (Swallow, McCartney & Millard, 1974) to years (Freeland, Rhines & Rossby, 1976).

The former reference is to a ship based tracking system of limited duration and spatial coverage, the latter refers to neutrally buoyant floats tracked over a wide area of the western basin of the North Atlantic by the use of land based listing stations and acoustic signals transmitted via the SOFAR axis (a minimum in the sound velocity profile at around 1200 m depth which enables sound to be carried over many hundreds of km with relatively small attenuation). The restriction of this technique to observations within ±500 to 1000 m of the SOFAR axis (depths of 700-2000 m) is a serious one but the ease with which very long studies of flow patterns may be made makes such a technique particularly attractive for the general understanding of circulation processes within an area (fig. A9).

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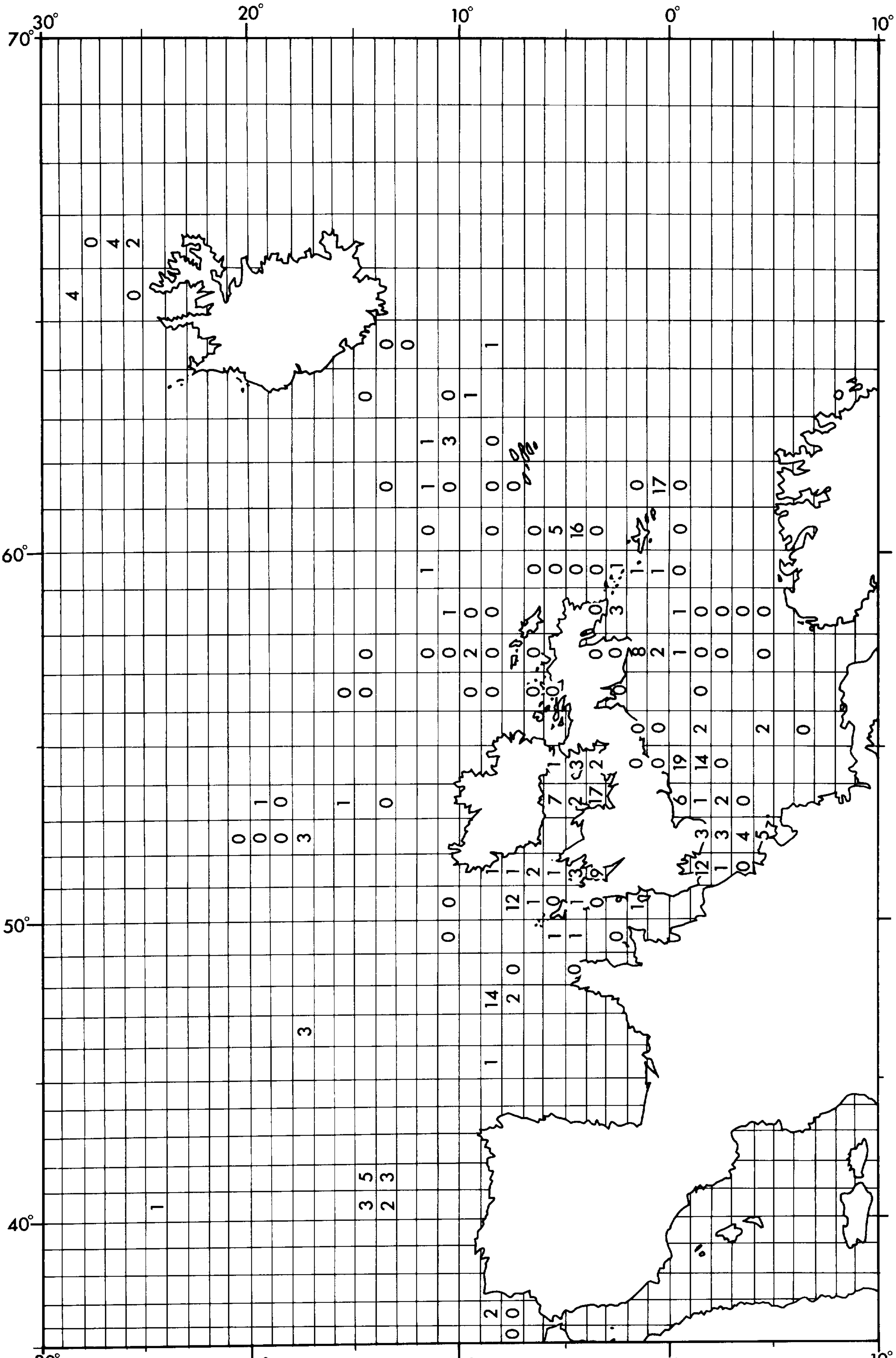


Fig 1

Table A1

Motion	Period	Horizontal wavelength	Vertical wavelength	Typical amplitude cm/sec	Geographical area
Mean flow		Various	h (waterdepth)	0- 10	Everywhere
Climatic change	10 yrs	Global	h	?	Everywhere
Seasonal variability	1 yr	Global	h	?	Everywhere
Mesoscale activity	30-100 days	400 km	h	5-100	All deep oceans
Meteorological disturbances	Aperiodic	Basin wide in shelf seas	h	100	Shelf seas and upper layer of ocean
Shelf and edge waves	2- 10 days	10 km cross slope 500 km along slope	h	5- 10	On topographic features e.g. seamounts, shelf edges, etc.
Inertial oscillations	12 hrs Sin (latitude) 0.5-5 days	10s of km	100 m	5- 50	All seas and oceans
Tidal oscillations	0.5-1 day	Basin width	h	10- 20 deep sea 10-200 shelf seas	Everywhere
Internal waves	Internal period	1 km	100 m	5	Throughout the stratified ocean
Surface waves	1-20 secs	100 m	Limited to upper 30 m of water column	200	Everywhere
Small scale	100 Hz	cm	cm	cm/sec	Everywhere dependent on stability

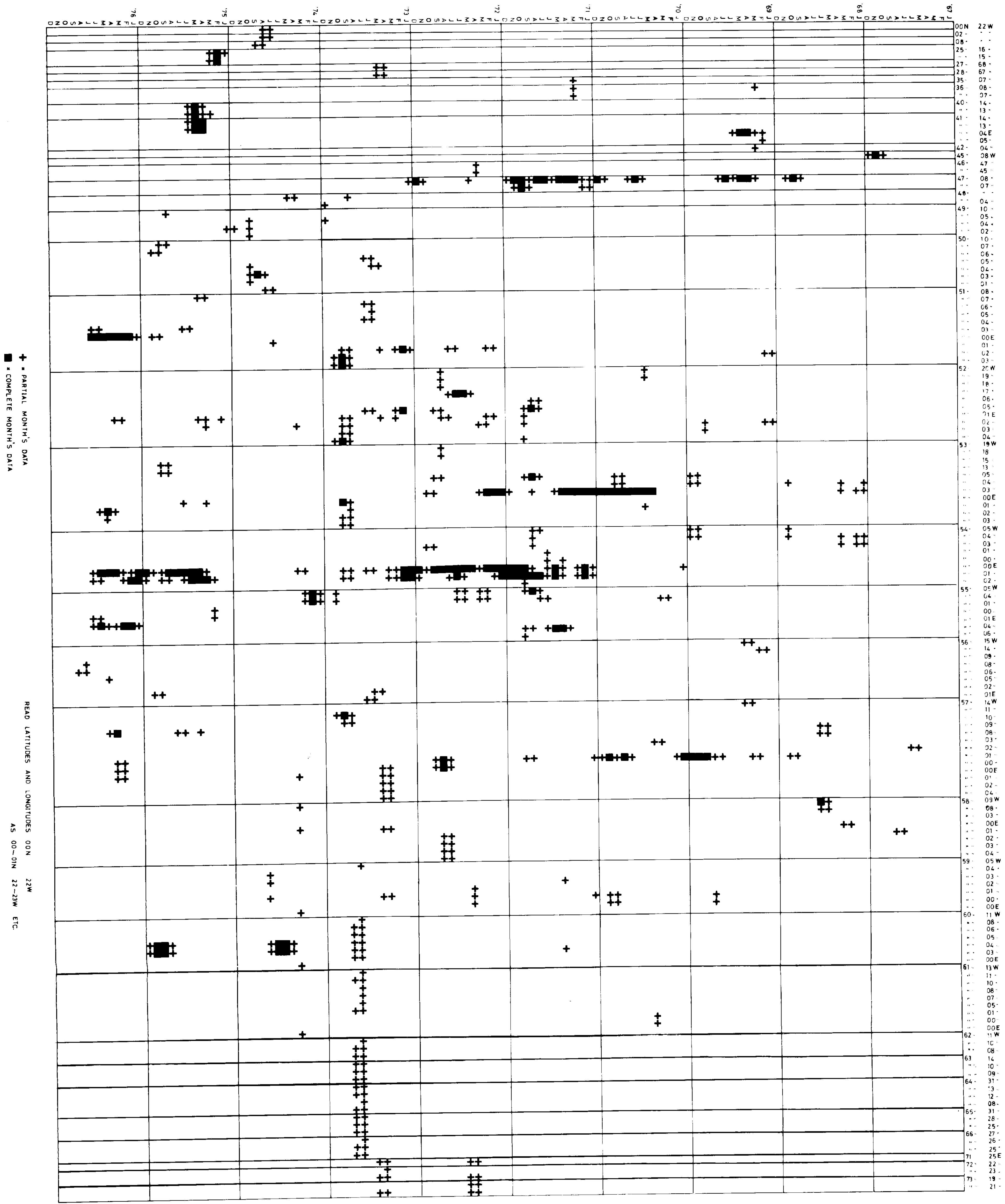

+ = PARTIAL MONTH'S DATA
■ = COMPLETE MONTH'S DATA
READ LATITUDES AND LONGITUDES 00N 22W
AS 00–01N 22–23W ETC.
'76
'75
'74
'73
'72
'71
'70
'69
'68
'67
J F M A M J J A S O N D
00N 22W
52 20W
53 19W
54 05W
55 05W
56 15W
57 14W
58 09W
59 05W
60 11W
61 13W
62 11W
73 21

fig.2

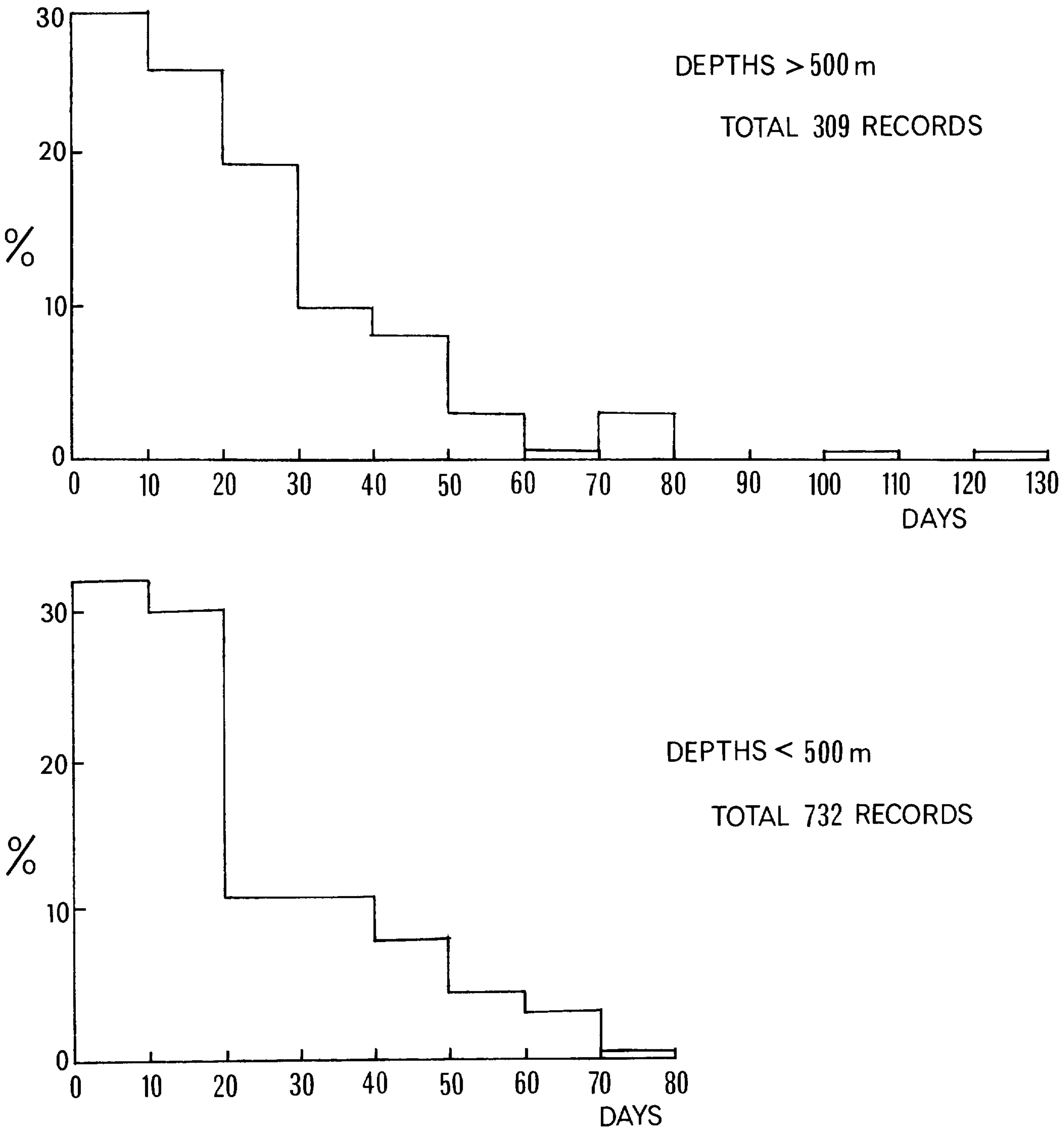
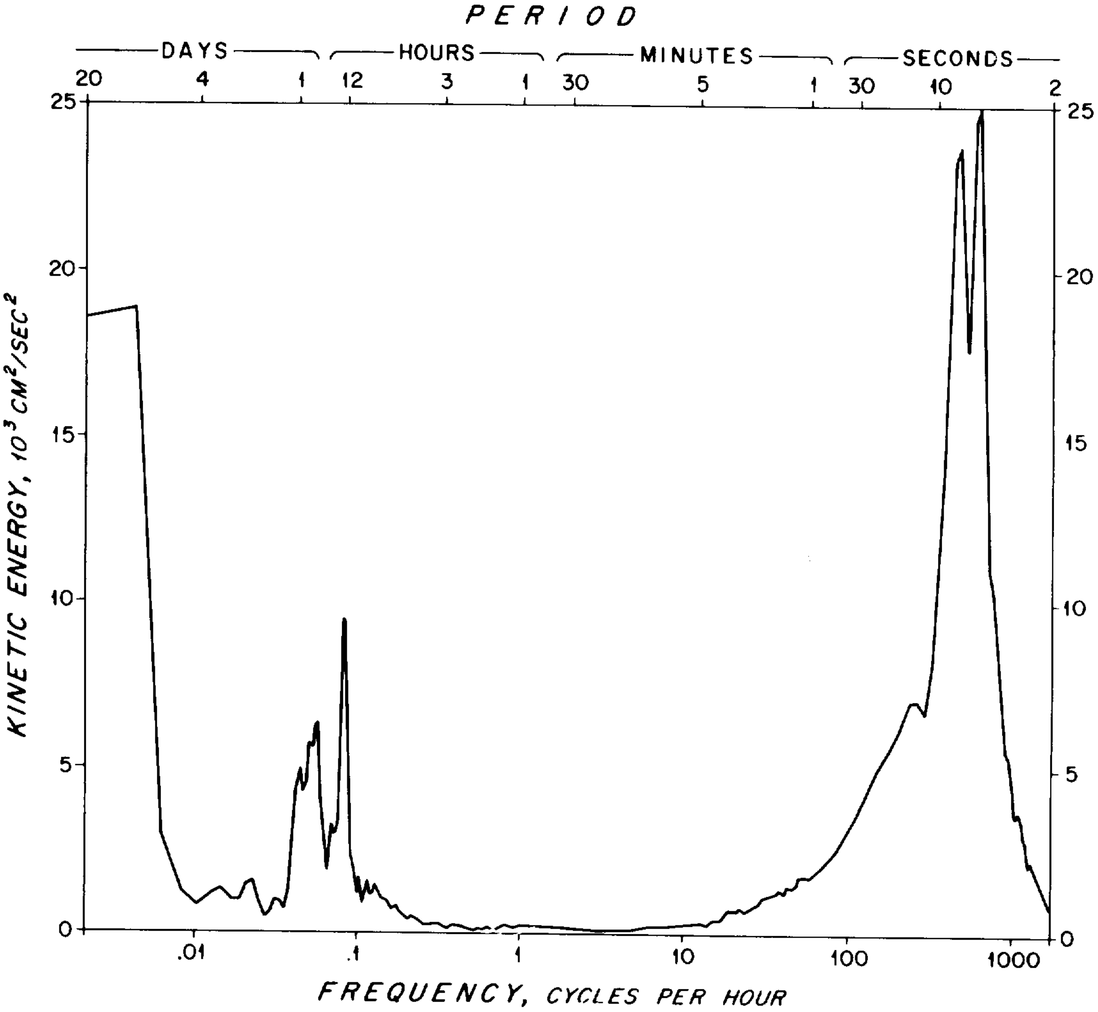

DEPTHS > 500 m
TOTAL 309 RECORDS
%
0
10
20
30
0
10
20
30
40
50
60
70
80
90
100
110
120
130
DAYS
DEPTHS < 500 m
TOTAL 732 RECORDS
%
0
10
20
30
0
10
20
30
40
50
60
70
80
DAYS

Fig. 3


PERIOD
DAYS
HOURS
MINUTES
SECONDS
20
4
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3
1
30
5
1
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15
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5
0
KINETIC ENERGY, 10^3 CM^2/SEC^2
.01
.1
1
10
100
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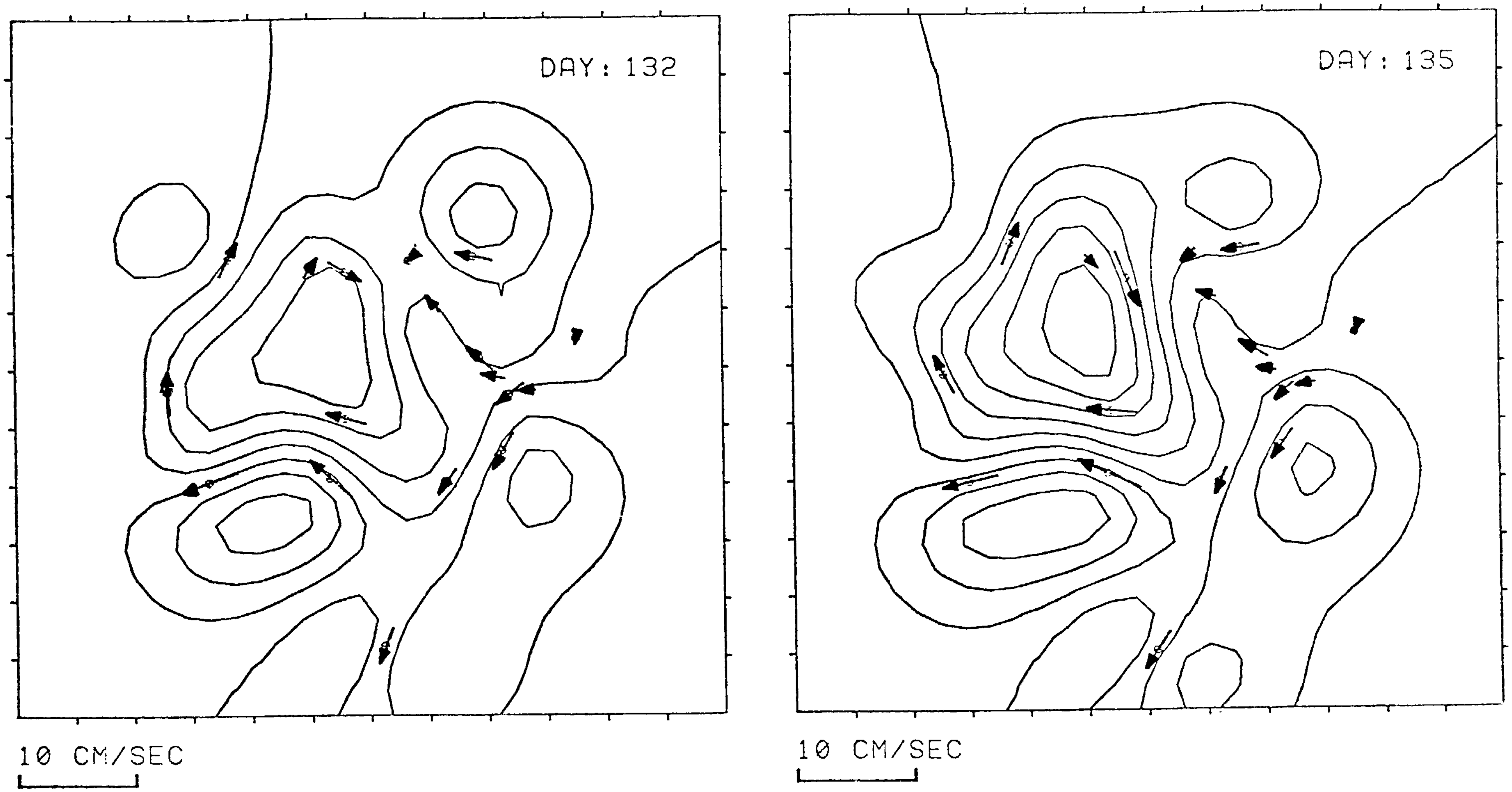
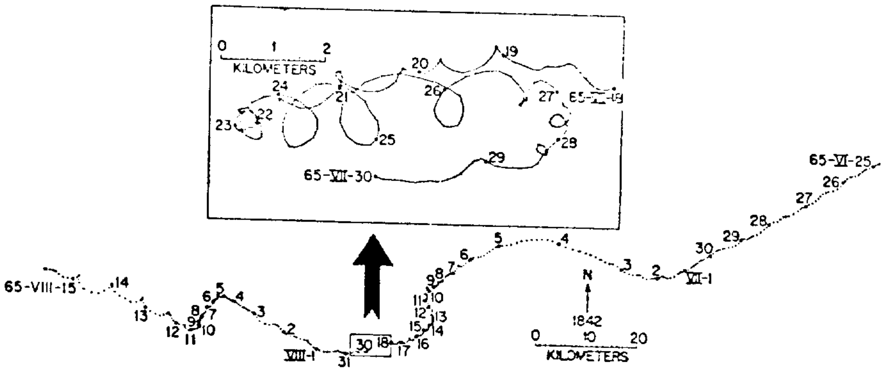
FREQUENCY, CYCLES PER HOUR

Fig. A1

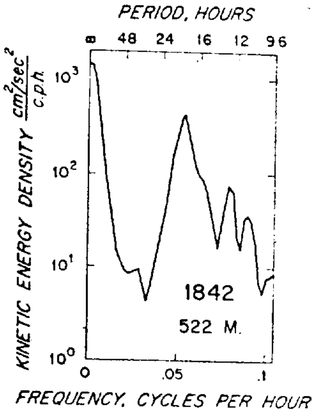


Stream Lines of mesoscale eddies at 1500m in the MODE experiment. (The box is 600 x 600 Km)

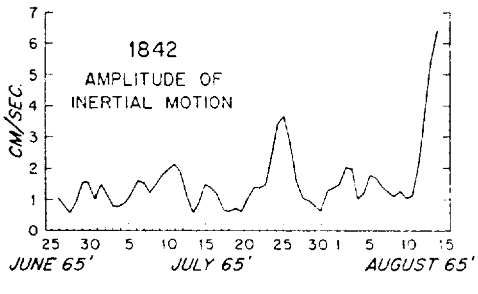
Fig. A2



A. Progressive vector diagram from 522m in 2000m of water. Expanded section shows inertial oscillations.

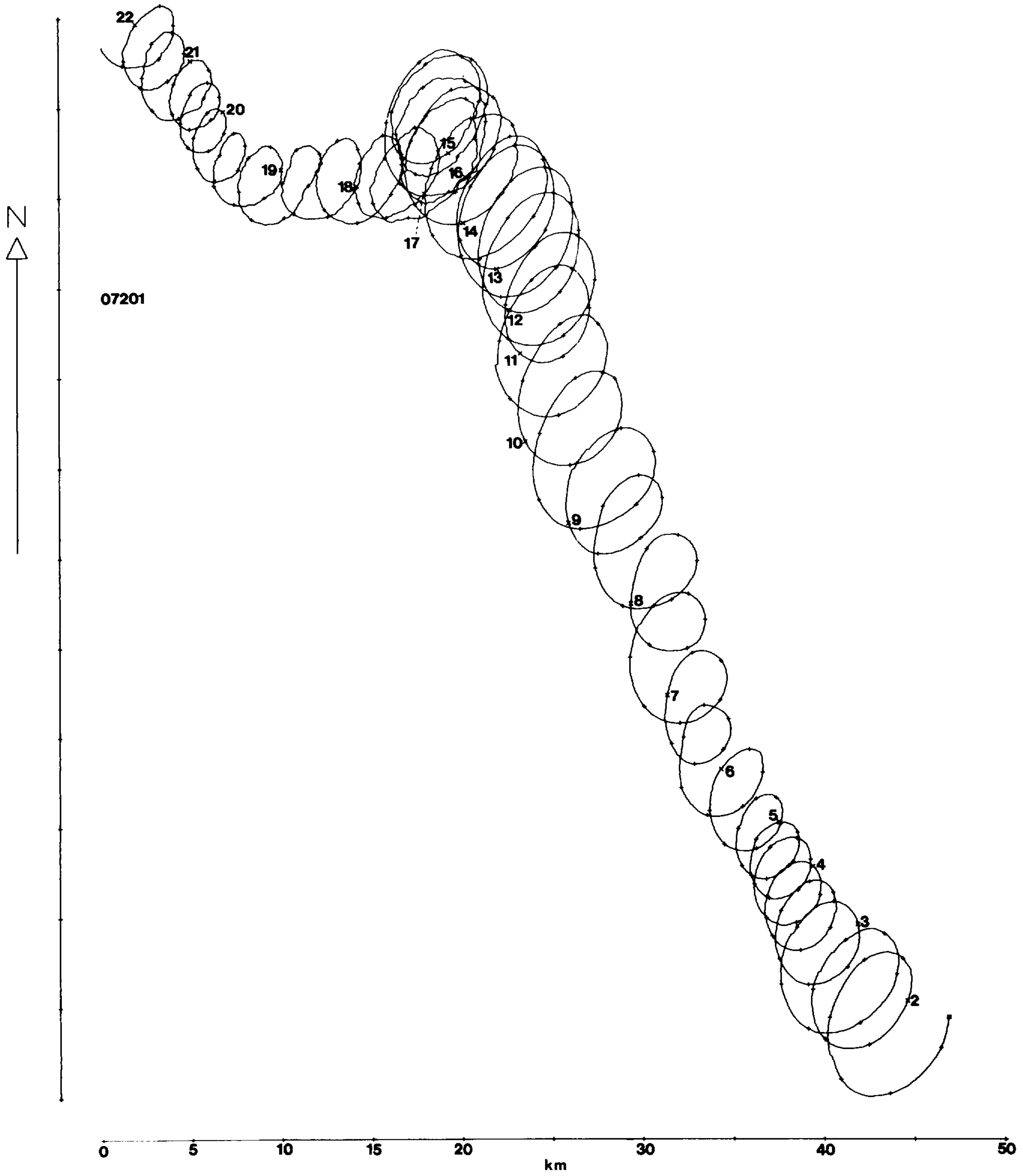


B. Kinetic energy spectrum from record shown in A. The peak is at the local inertial period of 19hrs.



C. The amplitude of the inertial period notions in the record. Note the increase in energy through the section expanded in A.

Fig. A3



Oscillations of semi-diurnal tidal period in a record.
In 200m. of water (Near 48°N 7°W)

Fig. A4

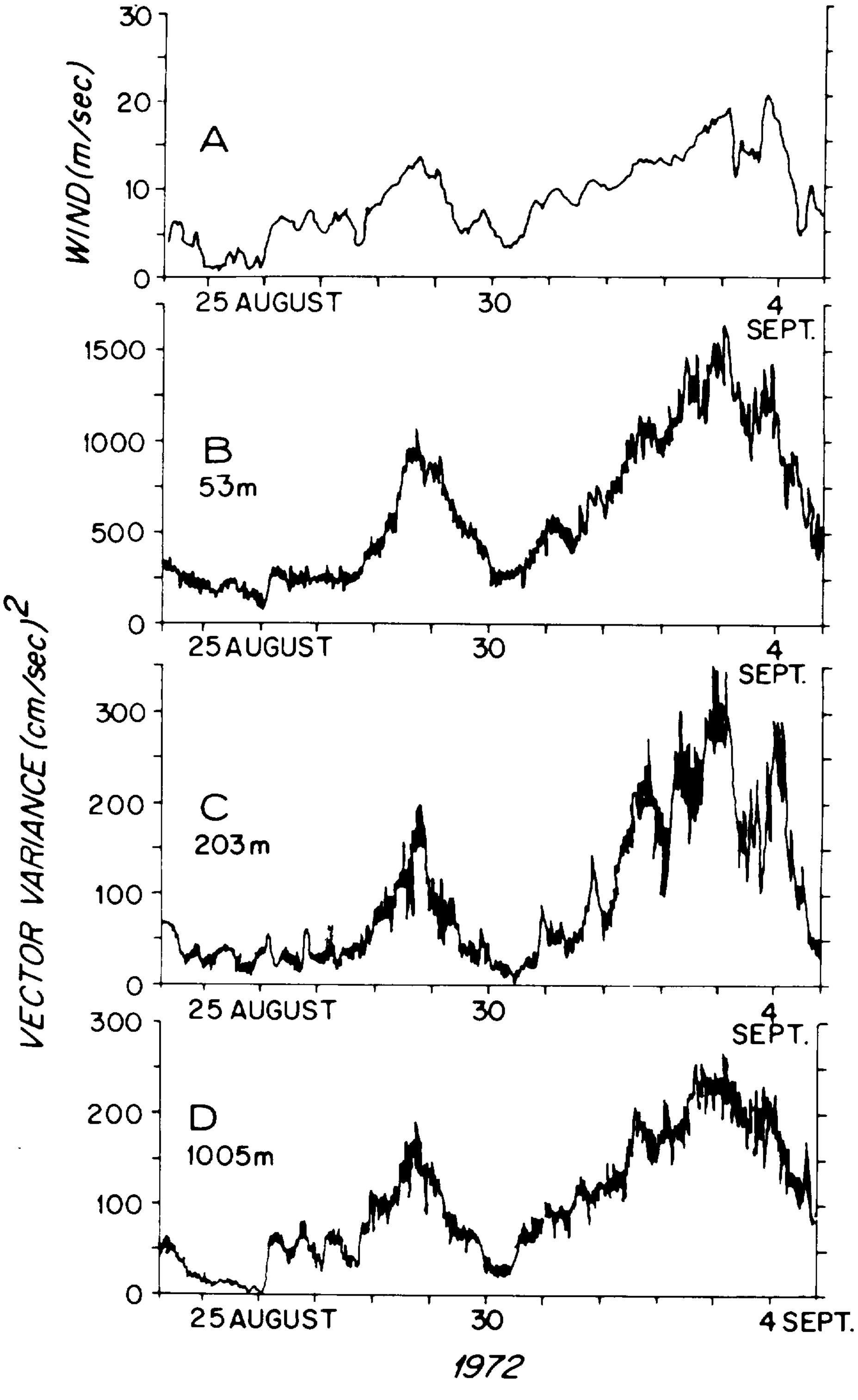


Fig. A5

An example of the influence of surface waves on a surface following buoy being transmitted down the mooring line. There is rapid attenuation in the upper layers (B to C) as the horizontal motions are damped but rather little decrease in the remaining energy between 200 and 1000m. The energy at all depths is closely related to surface wind speed A.

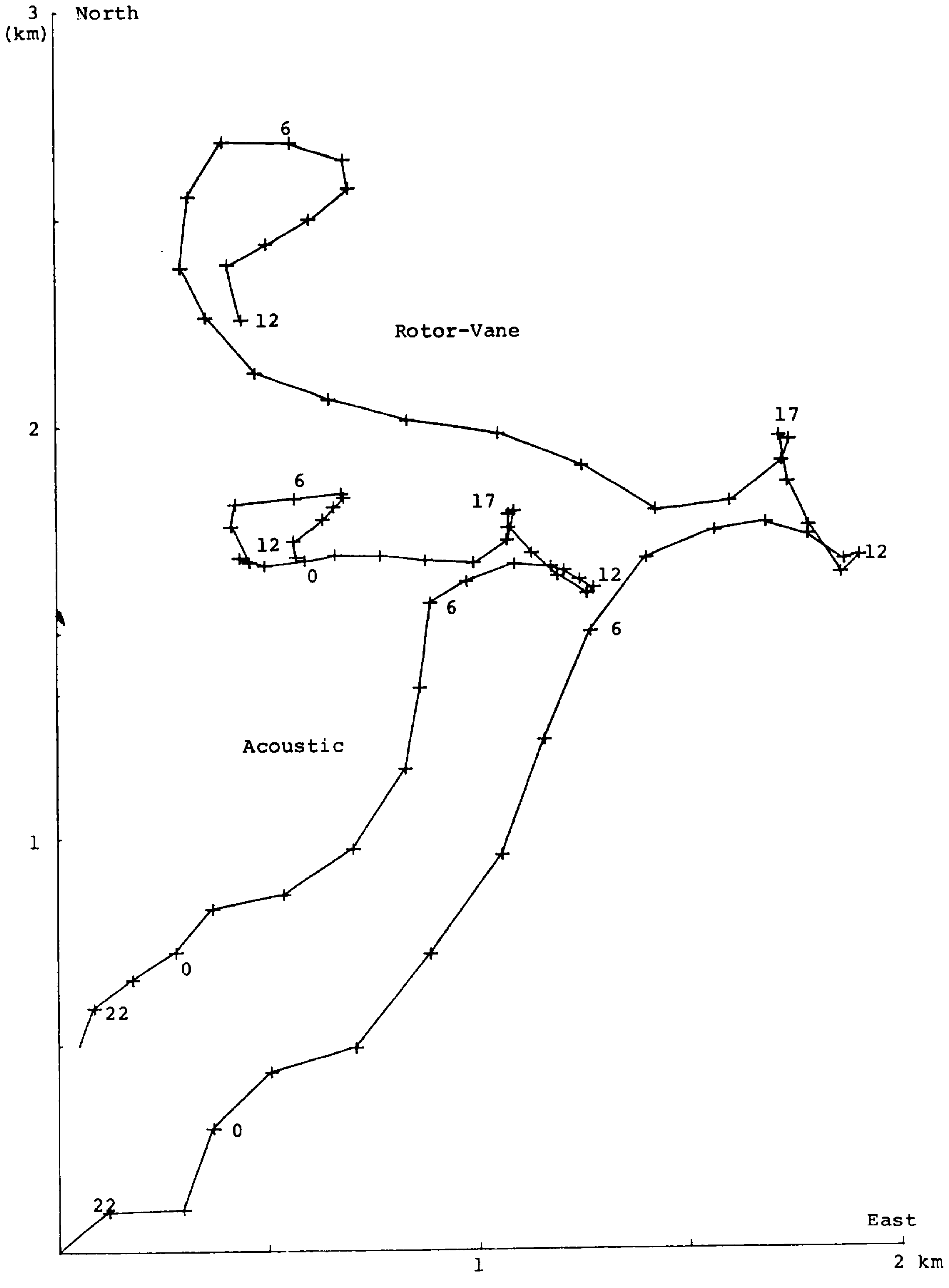
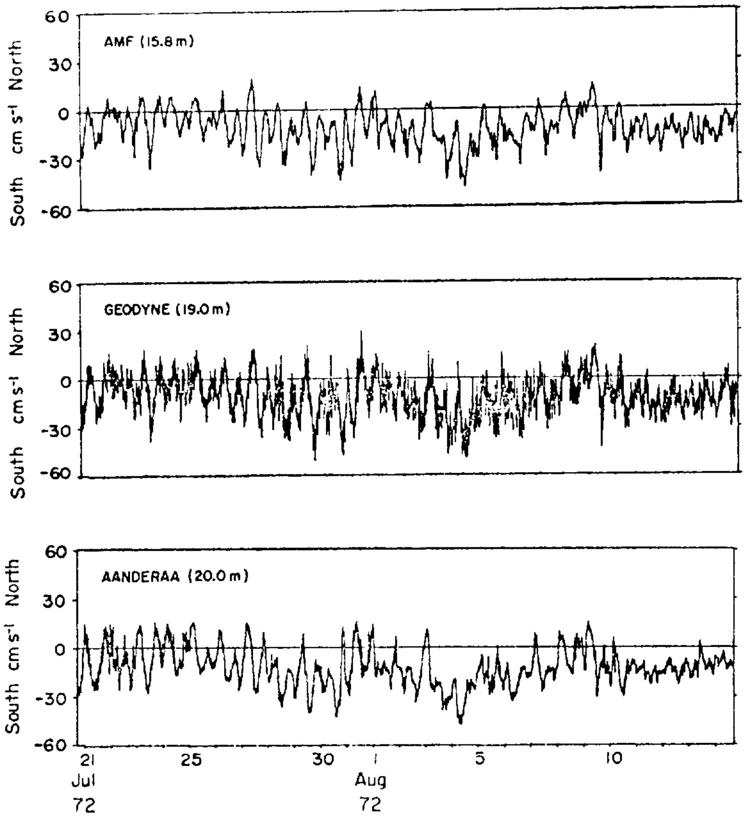
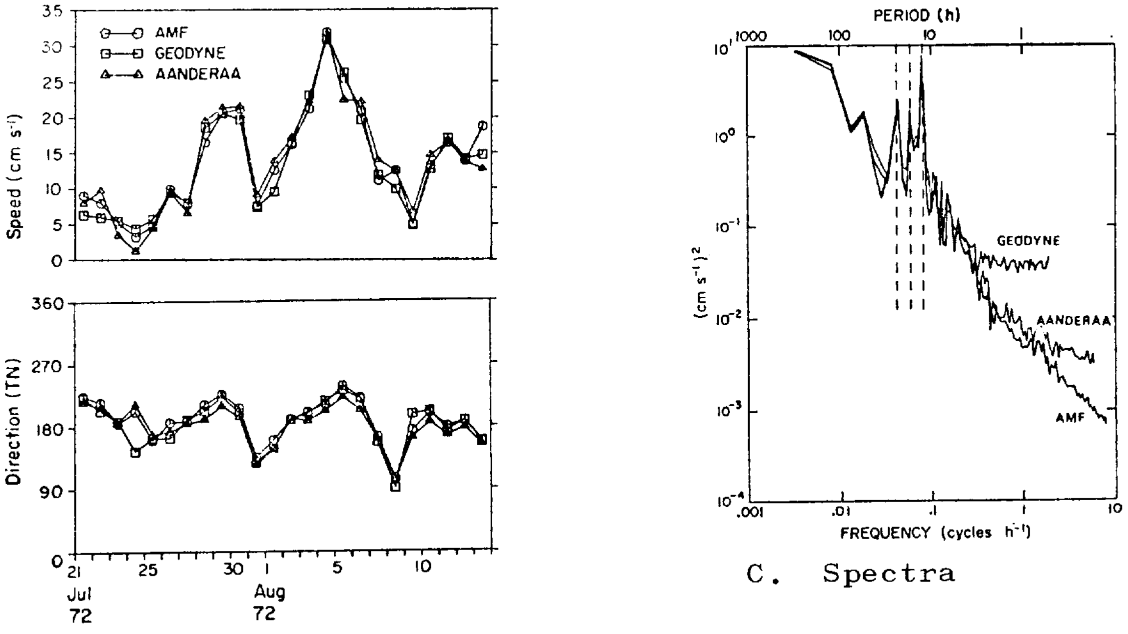

3
(km)
North
2
1
1
2 km
East
Rotor-Vane
Acoustic
6
12
17
12
6
12
0
17
12
6
6
0
22
0
22

Fig. A6



A. N - S Components

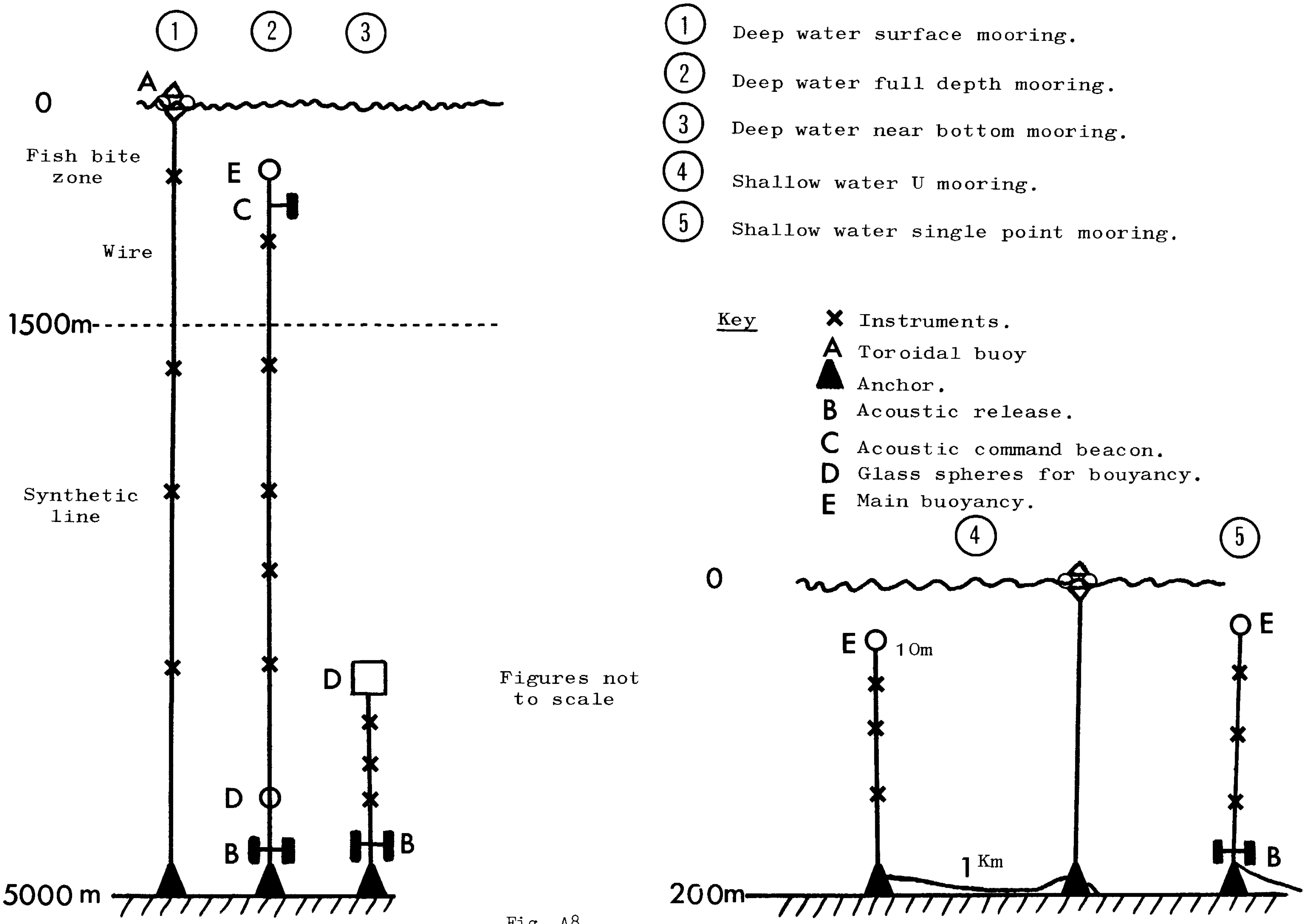


B. Speed & Direction

C. Spectra

Comparisons of current records by various types of instrument in shallow water.

Fig. A7



Figures not to scale

Fig. A8

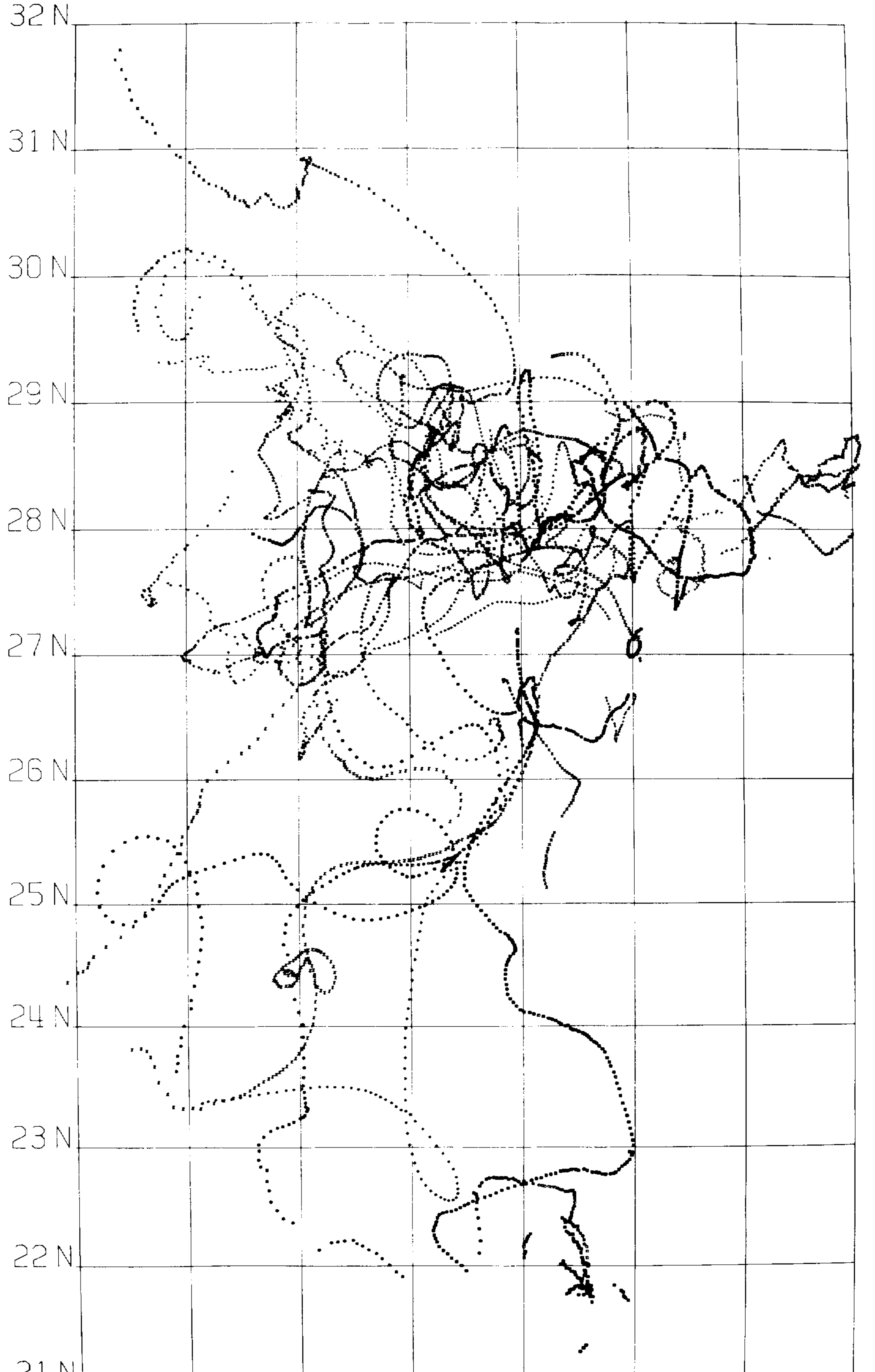

32 N
31 N
30 N
29 N
28 N
27 N
26 N
25 N
24 N
23 N
22 N
21 N
74 W
73 W
72 W
71 W
70 W
69 W
68 W
67 W

Fig. A9