Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Current Measurements in the Western Atlantic

N. P. Fofonoff and F. Webster

Phil. Trans. R. Soc. Lond. A 1971 **270**, 423-436
doi: 10.1098/rsta.1971.0082

Email alerting service Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click **here**

To subscribe to *Phil. Trans. R. Soc. Lond. A* go to: **http://rsta.royalsocietypublishing.org/subscriptions**

This journal is © 1971 The Royal Society

Downloaded from rsta.royalsocietypublishing.org

Phil. Trans. R. Soc. Lond. A. **270**, 423–436 (1971) [423]
Printed in Great Britain

Current measurements in the western Atlantic

By N. P. Fofonoff and F. Webster
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, *U.S.A.*

About 350 instrumented moorings have been set during the past decade to develop and exploit a technique of ocean-current measurement.

Nearly all the records are characterized by intermittent oscillatory motions with random changes of amplitude and phase near the local inertial frequency and at the semidiurnal tidal frequency. Local generation of inertial currents by winds has been observed in the surface mixed layer.

Above tidal frequencies the motion is irregular and nearly isotropic horizontally. The kinetic energy density decreases with frequency and depth, with considerable day-to-day fluctuations. At a given depth, the kinetic energy is remarkably constant when averaged over a month or longer, and varies only within a narrow range over a large extent of the Atlantic Ocean.

Below inertial frequencies, the kinetic energy density increases with decreasing frequency. The motions have stronger vertical coherence and larger horizontal scale.

Deep currents are dominated by the meandering of the Gulf Stream. Speeds up to one knot ($0.5\,\mathrm{m\,s^{-1}}$) are found near the bottom under the Stream.

North of the Gulf Stream, a 3-year average from intermittent records indicates a westward flow, approximately parallel to the continental shelf and bottom topography.

Introduction

Development of instrumented moored buoys at the Woods Hole Oceanographic Institution began in 1959 to obtain direct measurements of currents for the study of the general circulation of the ocean. The original objectives of the programme and mooring design considerations were described by Richardson, Stimson & Wilkins (1963). Activities from 1959 to 1965 were summarized by Fofonoff (1968). To date, about 350 moorings have been set in a variety of scientific and engineering experiments.

The discovery of a rich variety of time-dependent motions extending over all measureable time scales has forced a modification of the original objectives of the programme. In recent years, the emphasis has been on experiments to describe the characteristics of the variable flow components in both time and space. Only one site, 'site D' at 39° 20′ N, 70° W, has been occupied for sufficient time to obtain reasonably stable estimates of the mean flow components. For logistic reasons, the bulk of the measurements have been made in the western Atlantic. However, moorings in other regions have been set as opportunity permitted. Locations of mooring sites from which current data is available are given in figure 1.

Evolution of instruments and mooring hardware has been a continual process. The primary goal of obtaining survival of moorings at sea for 2 to 4 months exposure has been attained (Berteaux 1970). Improvement of hardware to extend the exposure period is continuing. Redesign of instruments to obtain higher accuracy of measurement and greater flexibility of operation is in progress.

Three general types of moorings have been developed for use in the programme. Moorings with surface floats to mount wind recorders and sensors for other atmospheric variables and to measure near-surface currents constitute the first type. These moorings extend through the entire depth of the ocean and are subjected to higher drag loads as well as wave action. Because of exposure to surface waves, these moorings have the lowest probability of survival. Except for

The Royal Society is collaborating with JSTOR to digitize, preserve, and extend access to
Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences.
www.jstor.org

Downloaded from rsta.royalsocietypublishing.org

engineering tests, exposure at sea is presently limited to 2 months. The size of surface floats is a compromise between buoyancy requirements and the limitations of shipboard handling gear. A schematic drawing of a surface float mooring is given in figure 2. A 'back-up' recovery system consisting of a series of glass spheres is included on each mooring to permit recovery of the mooring cable and instruments in case of failure.

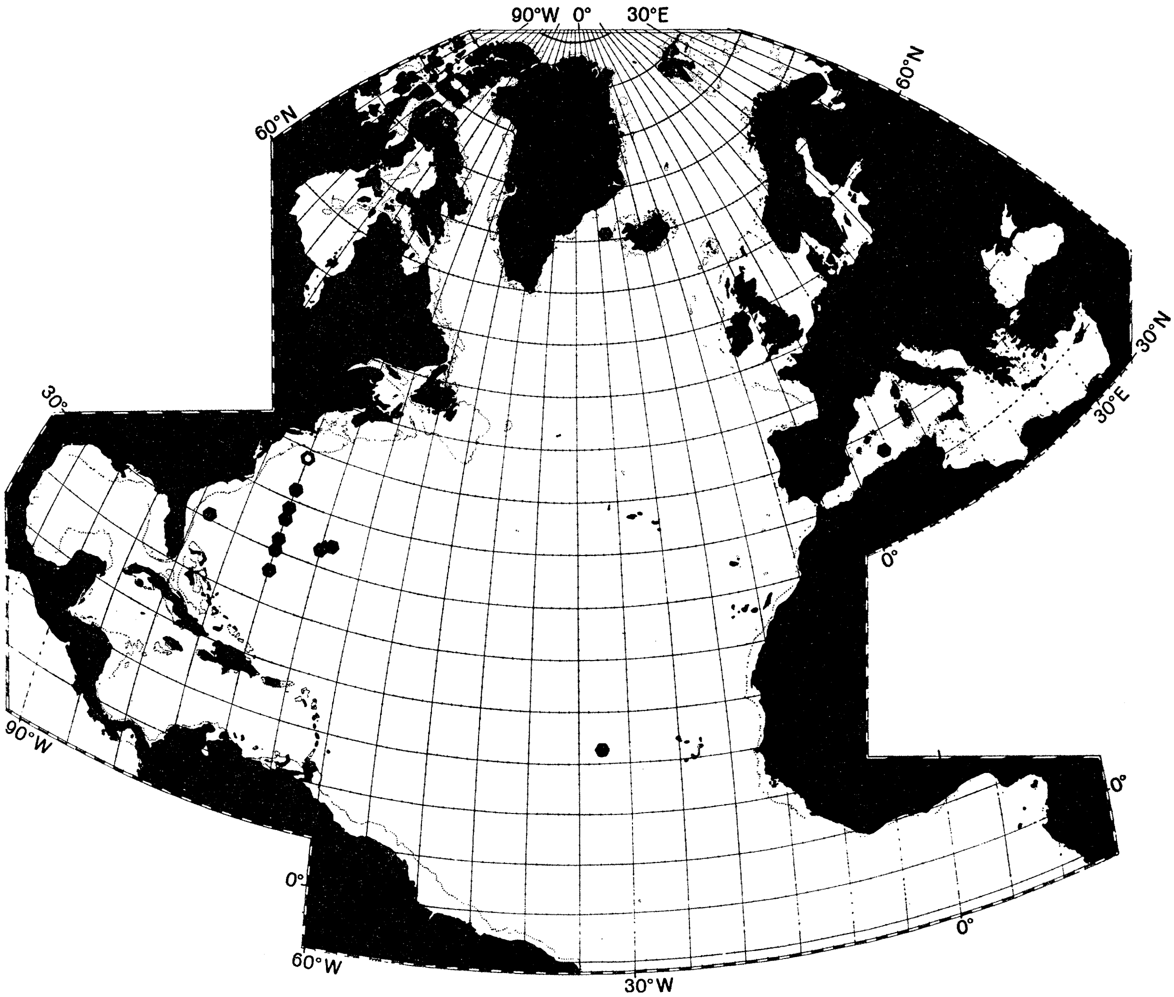

FIGURE 1. Location of mooring sites at which current meter measurements have been collected since 1965. Site D is marked with an open symbol.

The second type of mooring, shown in figure 3, is used for mid-depth measurements. Instruments and flotation modules are distributed along the mooring line to obtain optimum performance for the particular location. In some cases, floats and current meters have been set within 100 m of the surface in deep water. The third type (figure 4) consists of a flotation module, instrument package and an acoustic release. These 'bottom' moorings are used for measurements within a few hundred metres of the bottom. Because of their comparative low cost and high survival probability, bottom moorings are used more frequently than the other two types. The present programme of scientific experiments is biased toward studies of the water motion in deep and bottom layers of the ocean partially because of the higher overall capability of this type of mooring.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

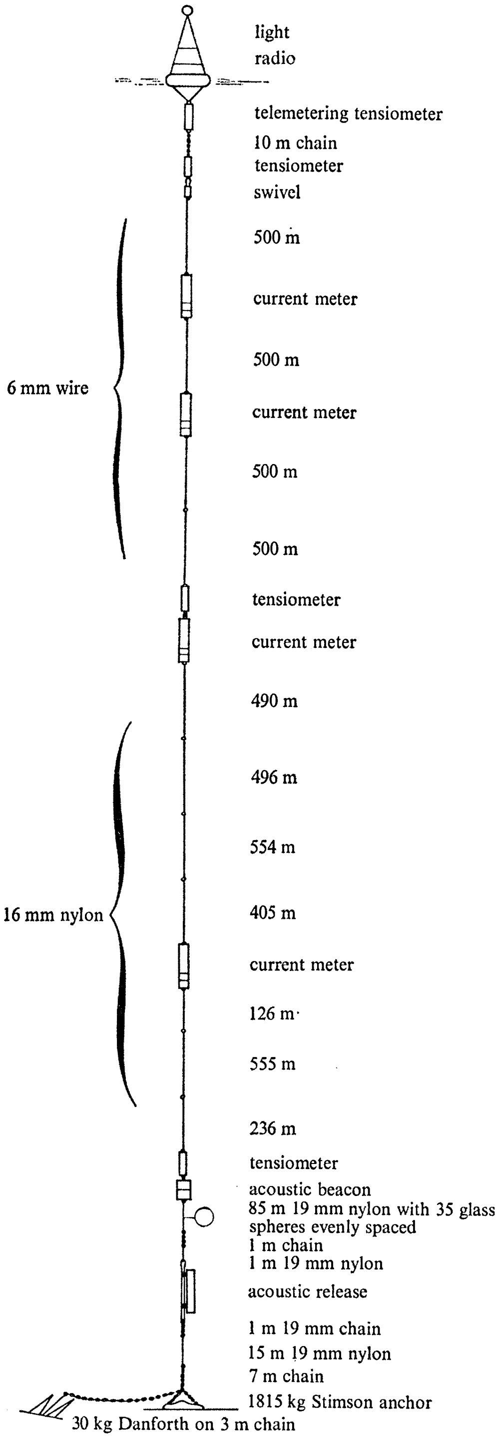

FIGURE 2. An example of a surface-float mooring. Station 323 was set in 5365 m of water at 33° 59′ N, 69° 58′ W, between 8 January and 13 May 1970.

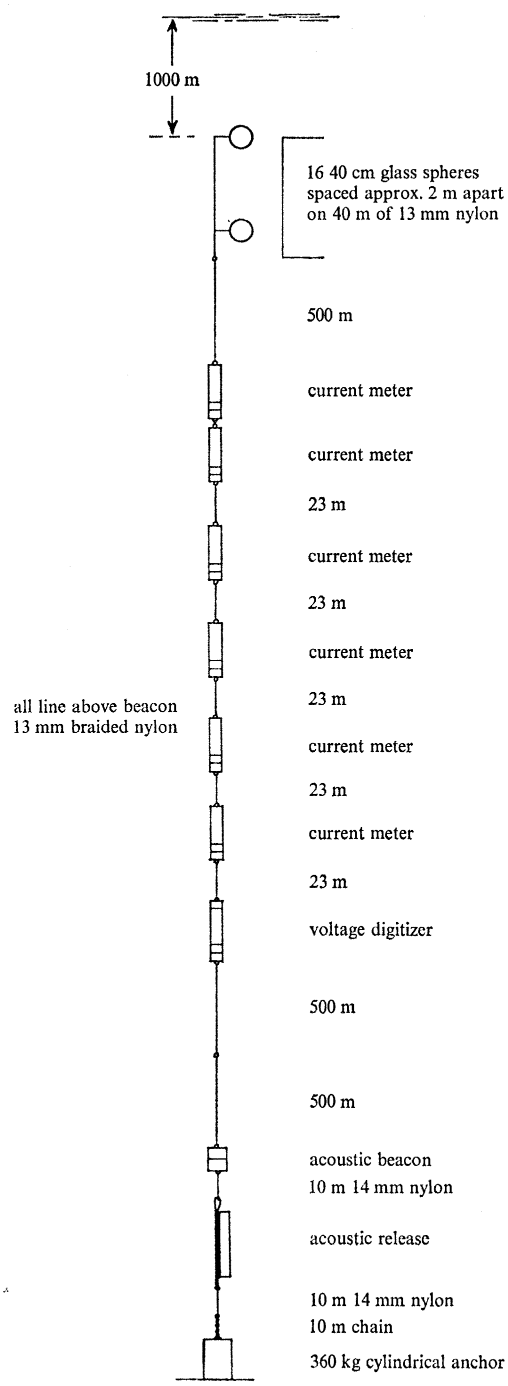

FIGURE 3. An example of a mooring with mid-depth buoyancy. Station 294 was set in 2674 m of water at site D, between 17 April and 26 April 1969.

Downloaded from rsta.royalsocietypublishing.org

All three types are instrumented with internally recording sensor packages, usually current meters. Telemetry to a central recorder or to shore has not been generally adopted in order to retain flexibility in assembling the various mooring configurations needed in experiments. Acoustic and radio telemetry is used for verification. location and release commands but not for data transmission.

Data files are maintained at the Woods Hole Oceanographic Institution. Summaries of each data series are circulated in the form of manuscript reports (Webster & Fofonoff 1965, 1966, 1967; Pollard 1970*b*). Arrangements are being made to deposit magnetic tape copies of all usable data files with the U.S. National Oceanographic Data Center.

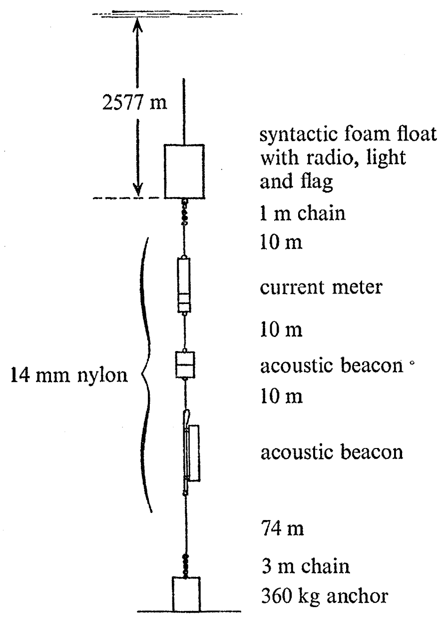

FIGURE 4. An example of a 'bottom' mooring. Station 302 was set in 2685 m of water at 39° 06′ N, 70° W, between 7 July and 11 October 1969.

DATA SAMPLING PROCEDURES

A mooring anchored in deep water is not a rigid, dynamically neutral, structure. The float, cable, and instruments are affected by waves, vortex shedding, and mooring drag of varying direction and magnitude. The induced motions degrade the quality of the measured current vectors. Moorings with surface floats exhibit the highest noise level because of their coupling to surface waves. The orbital motion of the waves excites the speed and direction sensors directly in the upper 20 m. Horizontal displacements of the surface float are transmitted as lateral motion of the cable and can be detected to at least 100 m. Vertical displacements are transmitted to great depth with little attenuation.

The standard sampling used in long-term measurements consists of a burst of N ($7 \leqslant N \leqslant 31$) measurements of speed and direction at a sampling rate of approximately 5 s. The burst of N vectors is repeated every 15 or 30 min. The purpose of burst sampling is to discriminate against high-frequency noise caused by waves and mooring motion and is effective because there is relatively low kinetic energy density between the internal wave frequencies and the high-

Downloaded from rsta.royalsocietypublishing.org

frequency surface wave frequencies (Webster 1967). A segment of a record is given in figure 5 to illustrate the sampling density. Because total storage capacity is fixed, record length can be increased by reducing the number of samples or by increasing the interval between sampling bursts.

The variance of the velocity components within each burst can be used to estimate a noise level for calculation of the spectrum of kinetic energy density. Under high noise conditions, produced by direct exposure of current meters to surface waves, the fluctuations of the 5 s vectors tend to become uncorrelated. Assuming that the energy of the resultant fluctuation of the vector average is spread uniformly across the spectrum as white noise, the spectral noise level density is

$$\tfrac{1}{2}[\overline{\mathrm{var}\,(u)+\mathrm{var}\,(v)}]/N\sigma_{\mathrm{Nyq}}$$

where $\overline{\mathrm{var}\,(u)}$ and $\overline{\mathrm{var}\,(v)}$ are the mean burst variances and σ_{Nyq} is the Nyquist frequency determined by the time interval between bursts. An example of noise level is shown in figure 6 for a

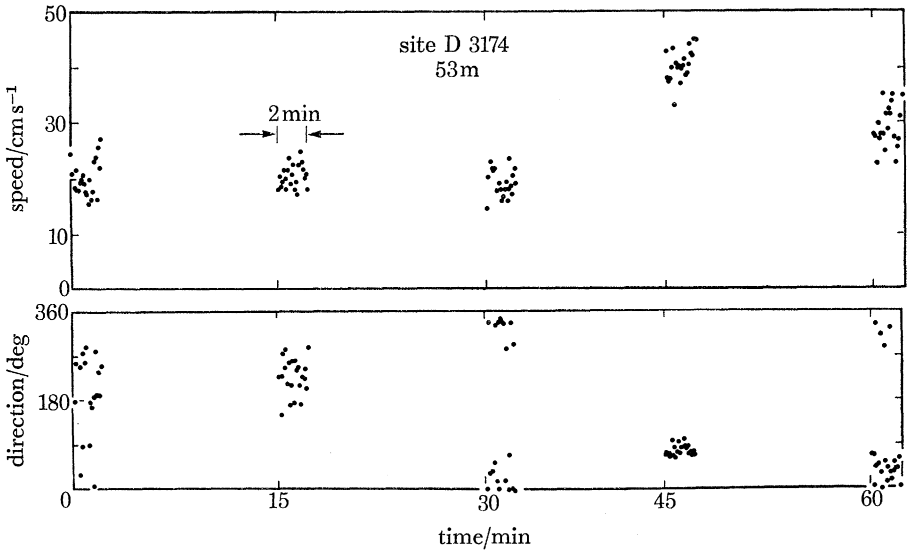

FIGURE 5. A sample segment from a current meter record collected at site D at a depth of 53 m. 22 samples per burst.

current meter at 13 m depth below a surface float. The burst noise here limits the spectrum at frequencies above 0.2 c/h. Simultaneous measurements at greater depths were not appreciably affected by burst noise.

The relationship of burst noise to surface waves can be inferred indirectly by comparing the standard deviation of the burst noise to wind speed in figure 7. The variation of noise amplitude with wind speed suggests that waves are the dominant noise generators. Except for the surface mixed layer, kinetic energy spectra appear to reflect real fluctuations throughout the observed frequency band. Low-frequency variations appear to be followed accurately even under high wave-noise conditions.

Subsurface moorings are immune to wave noise but have occasionally been observed to be excited in oscillation modes that appear to be coupled to vortex shedding from current meters (Fofonoff 1966).

At very low speeds ($<$ 5 cm/s), the threshold for the speed sensor (1.8 cm/s) and the quantizing

Downloaded from rsta.royalsocietypublishing.org

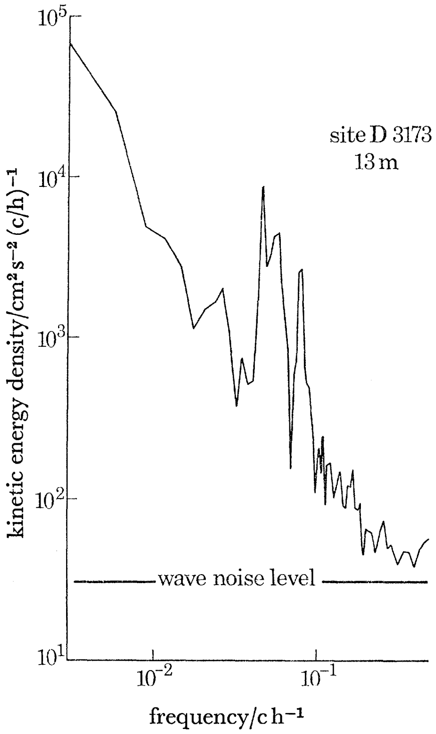

FIGURE 6. The kinetic energy density spectrum on a logarithmic scale for currents measured at 13 m depth at site D between 6 October and 18 November 1969. Because the density of sea water is 1 g cm^{-3}, the value of kinetic energy in ergs cm^{-3} is numerically the same as the velocity variance in cm^2 s^{-2}.

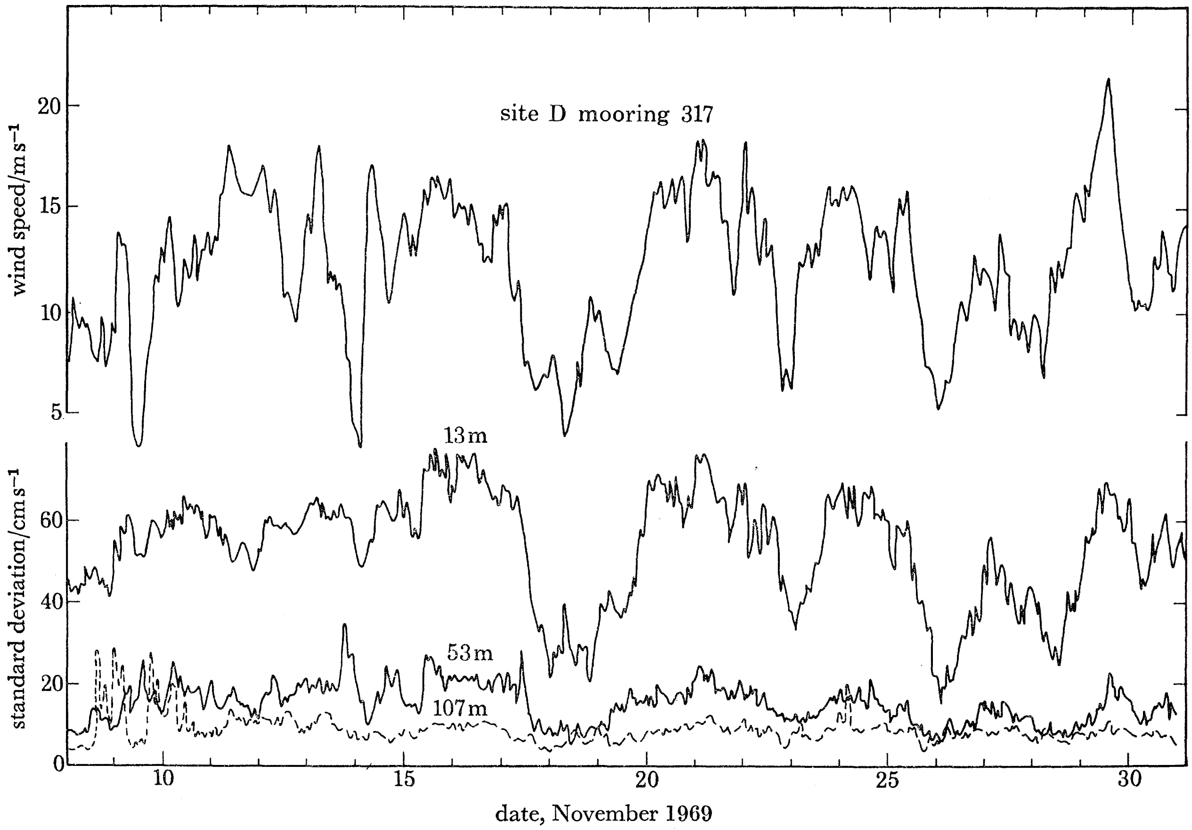

FIGURE 7. A comparison of wind speed with the 'burst noise' of the current meters. The standard deviation of each sample burst is shown for measurements at 13, 53, and 107 m depth.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

interval (0.5 cm/s) become limiting. Such low speeds are rare in the western Atlantic but have been a problem in the Mediterranean (Perkins 1970).

Reduction of burst noise can be achieved by increasing the number of measurements in the burst and extending its duration. An 'integrating' current meter designed to average vector components of the current is presently undergoing tests at Woods Hole. Recording of component averages will eliminate the need for storing voluminous burst data. The resultant increase in data storage capability will permit sampling of other variables with the same instrument.

Inertio-gravitational internal waves

The spectrum of kinetic energy has been calculated for time scales ranging from a few seconds to a few months. In the following review, those elements of the spectrum that have been of principal interest are discussed: first, the inertio-gravitational internal wave range, from the Coriolis frequency (period of about a day) to the Brunt–Väisälä frequency (period of about an hour); next those time-dependent processes that can be resolved having frequency less than the Coriolis frequency; and finally the mean properties and general circulation.

There is significant kinetic energy at all frequencies within the internal wave range of the spectrum, with pronounced peaks at inertial and tidal frequencies. Voorhis (1968) and Fofonoff (1969) have examined the internal wave spectra in terms of linear theory. However, above tidal frequencies the spectrum must be affected strongly by Doppler shifts caused by strong low-frequency components and by the large vertical shear of the mean flow. Frankignoul (1970) has examined the effects of weak vertical shear on a plane internal wave. The rotation of internal waves by the shear tends to shift energy into inertial currents. The resultant spectrum is not dissimilar from that observed in the ocean.

In general, above the semi-diurnal frequency, the horizontal kinetic energy appears to form a continuum that drops as the $-\frac{5}{3}$ power of frequency. This power law dependence is continuous through and above the Brunt–Väisälä frequency and, although it is difficult to determine the 'true' energy spectrum in the presence of mooring noise, it apparently occurs up to the highest frequency to which the current meters can respond (about 1 Hz).

The similarity between a $-\frac{5}{3}$ power law in frequency and the $-\frac{5}{3}$ power law in wavenumber resulting from Kolmogorov's hypothesis of homogeneous isotropic turbulence has led to an exploration of the consequences of interpreting this part of the spectrum in terms of turbulence (Webster 1969*b*). While estimates of the rate of energy dissipation thus obtained are physically reasonable it is unsatisfactory to assume that a process that demonstrably satisfies inertio-gravitational dynamics in a stratified fluid (Fofonoff 1969) is isotropic turbulence. It seems more likely that the results might be explained in terms of nonlinear energy transfers in a spectral continuum of internal waves. Such a continuum could conceivably maintain a spectrum with a $-\frac{5}{3}$ power dependence on wavenumber, since Kolmogorov's results are based on dimensional arguments. Further investigation needs to be directed to an investigation of mechanisms for transfer of kinetic energy between internal waves of differing wavenumber/frequency.

Fluctuations in the kinetic energy level of currents occur on a time scale of a few days over the entire band of frequencies. An example of variation of the amplitude and phase of inertial and tidal oscillations is given in figure 8. It can be seen from figure 8 that variations of the inertial and tidal fluctuations are not correlated with each other. Pollard (1970*a*) and Pollard & Millard (1970) have examined the excitation of inertial currents by local winds in the surface mixed layer.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

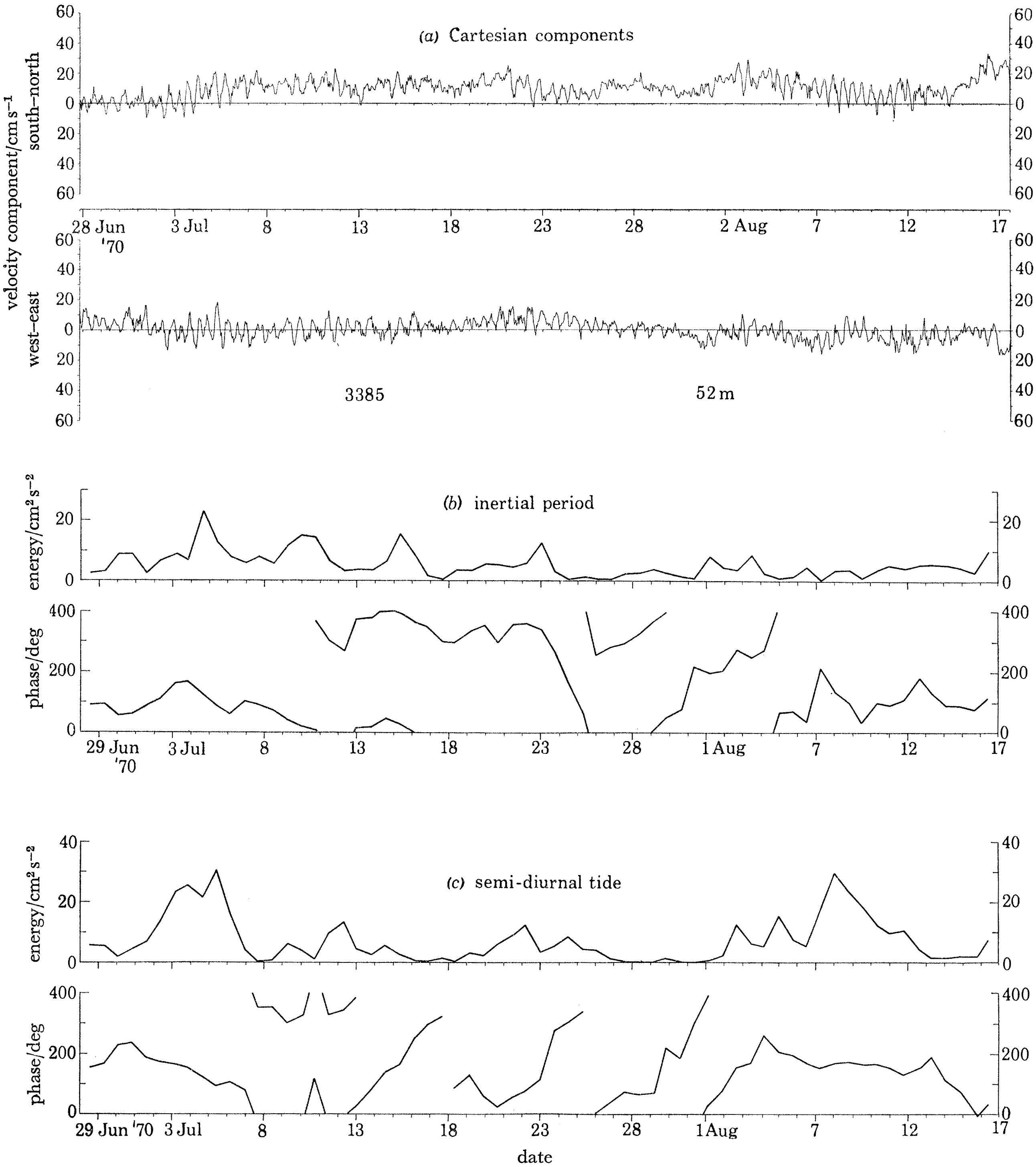

FIGURE 8. (*a*) The Cartesian components of velocity measurements from 52 m depth at site D. Note the presence of dominant variable oscillations of about 1-day period and the superposed variations on a wide range of time scales. (*b*) The amplitude of inertial-period (upper) and (*c*) semi-diurnal tidal (lower) motion for the data presented in (*a*). Note the apparently random fluctuations in the amplitude and phase of each and the lack of correlation between the two processes.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

Although a good correlation exists, particularly in strong local generation conditions, the presence of inertial currents below the mixed layer is not satisfactorily explained. The kinetic energy fluctuations above tidal frequencies do not appear to be correlated to inertial or tidal variations or to variations of the mean flow. Lack of strong correlations across frequencies has hampered interpretation of the high-frequency fluctuations in terms of their generating mechanisms.

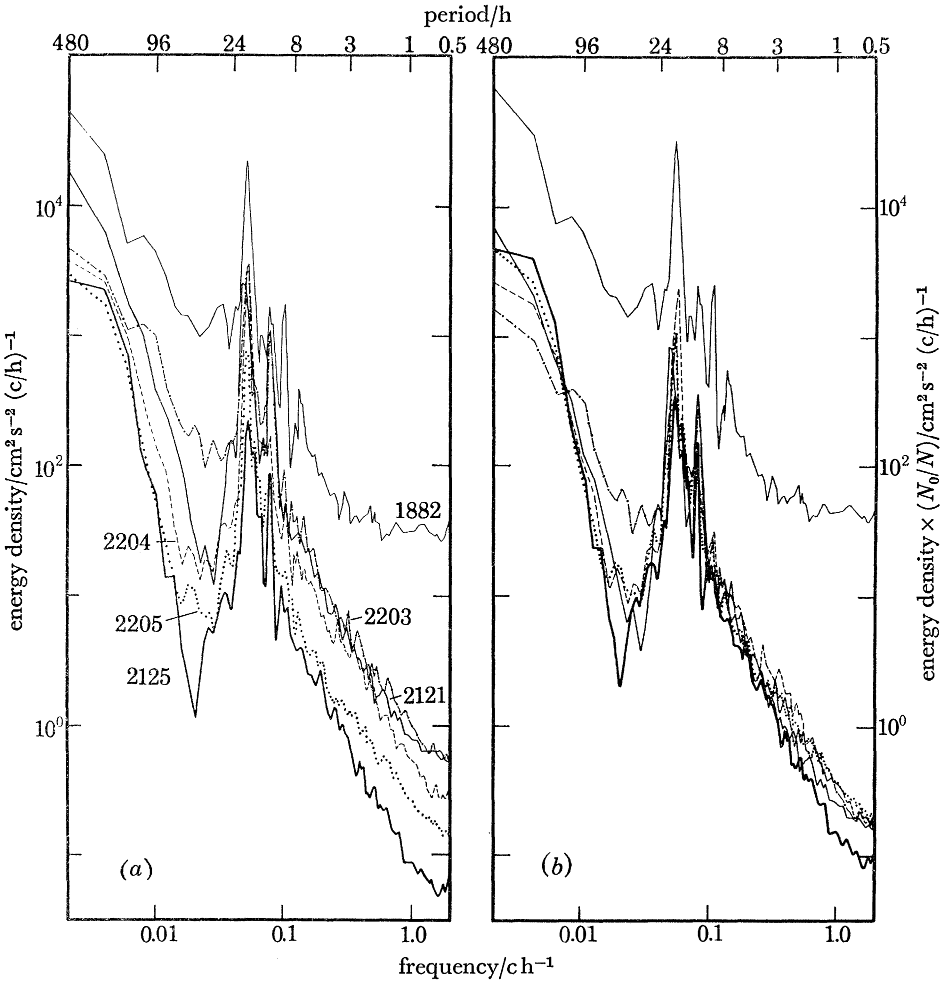

FIGURE 9. (*a*) Kinetic energy density spectra over a set of depths at Site D. (*b*) The same spectra, normalized by the local Brunt–Väisälä frequency. N_0 was chosen as 1 c/h. The records used are:

1882, 7 m, 6 Oct. to 23 Nov. 1965, $N = 0.70$ c/h.
2121, 50 m, 8 Oct. to 7 Dec. 1966, $N = 3.12$ c/h.
2203, 106 m, 26 Feb. to 11 Apr. 1967, $N = 3.03$ c/h.
2204, 511 m, 26 Feb. to 11 Apr. 1967, $N = 1.48$ c/h.
2205, 1013 m, 26 Feb. to 11 Apr. 1967, $N = 0.66$ c/h.
2125, 1950 m, 8 Oct. to 18 Nov. 1966, $N = 0.58$ c/h.

If long-term averages of horizontal kinetic energy are computed, the short-term fluctuations are smoothed out and energy levels are found to converge to values that are a function of frequency and depth. The vertical profile of the long-term mean values, at least beneath the surface mixed layer, is proportional to the vertical profile of the Brunt–Väisälä frequency (Webster 1969*a*). In figure 9, spectra at several depths at site D are compared. Dividing each spectrum by the local

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

Brunt–Väisälä frequency removes most of the variation with depth. Such a dependence on depth can be expected if there is an efficient transfer of energy through the vertical water column.

Remarkably, the levels of kinetic energy in the internal wave range estimated from long-term averages do not appear to vary widely with geographic location (Webster 1971). The kinetic energy at mid-depths at site D is within a factor of two of that at the same depth at other locations such as the Bermuda region, the Bay of Biscay, the Mediterranean, and the tropical Atlantic. Further study is needed to define energy-limiting or saturating processes that might control or stabilize the climatological kinetic energy levels. As further observations of ocean currents become available, patterns of departure of kinetic energy from the mean over short time periods or over local regions should help clarify the nature of mechanisms providing energy sources and sinks.

Current measurements at internal wave frequencies are coherent over some local volume of the ocean. In general, deep-sea moorings must be separated widely enough to avoid tangling during setting. The resulting horizontal distances (usually a kilometre or more) are in practice too great for the currents to be coherent over the inertio-gravitational range of frequencies, except possibly at inertial and tidal frequencies. Vertical separations are physically much easier to obtain and control (Siedler 1971). The results obtained so far show that coherence is apparently a function of vertical separation at a given frequency. In general, currents are coherent vertically over some range of low frequencies and incoherent over some higher range of frequencies. The transition from the coherent to the incoherent range is not sharp, but it is usually possible to define some transition frequency. Preliminary results indicate that the frequency of transition (the maximum coherent frequency) drops inversely as the vertical separation of the measurements. Above the Brunt–Väisälä frequency, the scale of vertical coherence drops sharply. If the maximum coherent frequency is to lie in the internal wave range, the vertical separation must generally be less than 200 m, again with possible exceptions at inertial and tidal frequencies.

Low-frequency currents

Low-frequency ocean currents are here defined as those with frequencies less than the inertial frequency. To continue with the discussion of scales of coherence of the previous section, below the inertial frequency the maximum coherent frequency continues to drop inversely with vertical separation. A notable exception is that currents are less coherent over a region of abrupt change in density, and coherent currents are usually not observed over vertical separations that span the near-surface seasonal thermocline.

Quantitative estimates of horizontal coherence are more difficult to obtain than for vertical coherence because of the greater difficulties in obtaining simultaneous records. A few sets of measurements have been obtained that show apparent low-frequency coupling or coherence between widely separated points of observation.

The example of figure 10 shows the integrated N–S component of velocity near the surface both at site D and at site J (36° N). These measurements were obtained on either side of the Gulf Stream and suggest a possible coupling with the Stream itself. Such evidence has stimulated further work, and recently Schmitz, Robinson & Fuglister (1970) made near-bottom ocean current measurements extending north–south over a 250 km distance that straddled the path of the Gulf Stream. They found that time-dependent current fluctuations with a period of about 30 days were coupled with fluctuations in the surface position of the Gulf Stream. Furthermore,

Downloaded from rsta.royalsocietypublishing.org

the low-frequency fluctuations were coupled both across the extent of the deep array and with surface measurements at site D.

Low-frequency currents show an interaction with bottom topography. At site D, which is about 50 km south of the Continental Slope, the amplitude of the north–south component of low-frequency fluctuations is less than that of the east–west component below the depth of the Continental Shelf. It has been inferred from this (Webster 1969*a*) that the Continental Shelf, which runs east–west in this region inhibits the north–south amplitude of low-frequency fluctuations. Above the depth of the Continental Shelf, low-frequency motions are apparently horizontally isotropic.

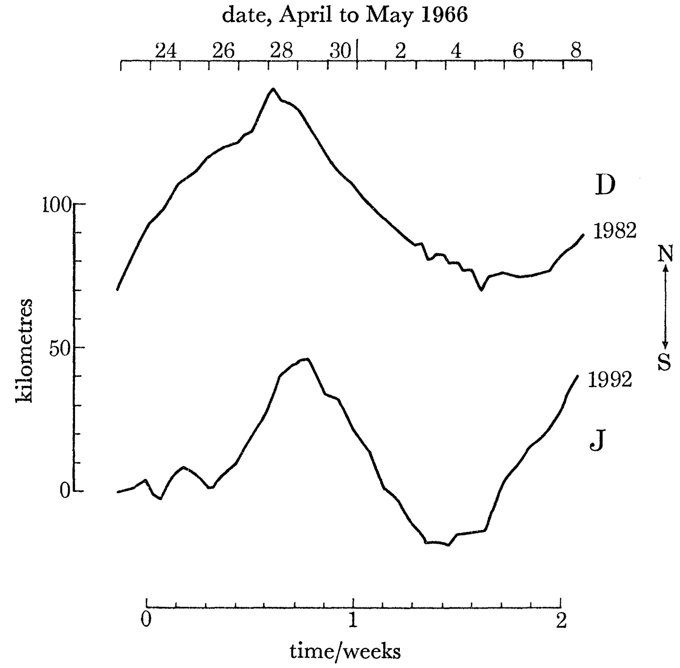

Figure 10. The integrated north–south component of velocity at site D (latitude 39° 20′ N) and site J (latitude 36° N). Note the apparent in-phase coupling between the two positions, separated by 370 km along the 70° W meridian. The Gulf Stream is between the two sites.

Thompson (1971) further examined the properties of low-frequency current fluctuations at site D. He found that the currents tended to occur along a preferred axis (113°–293°). A further analysis was carried out by Thompson using a numerical model, from which he concluded that the low-frequency currents may be Rossby waves driven by the Gulf Stream, to the south. The preferred direction of motion was ascribed to the concentrating effect of the change in water depth as the waves moved northward from the Gulf Stream region.

Thompson used a method of estimation from time series with random gaps to obtain estimates of the energy spectrum at very low frequency. An example (figure 11) at 100 m shows that the energy may not continue to increase at progressively lower frequencies. Furthermore, below the inertial frequency no persistent spectral peaks are found. There is generally a relative minimum of energy in the range of frequencies from one cycle per day to about one cycle every 5 days.

Downloaded from rsta.royalsocietypublishing.org

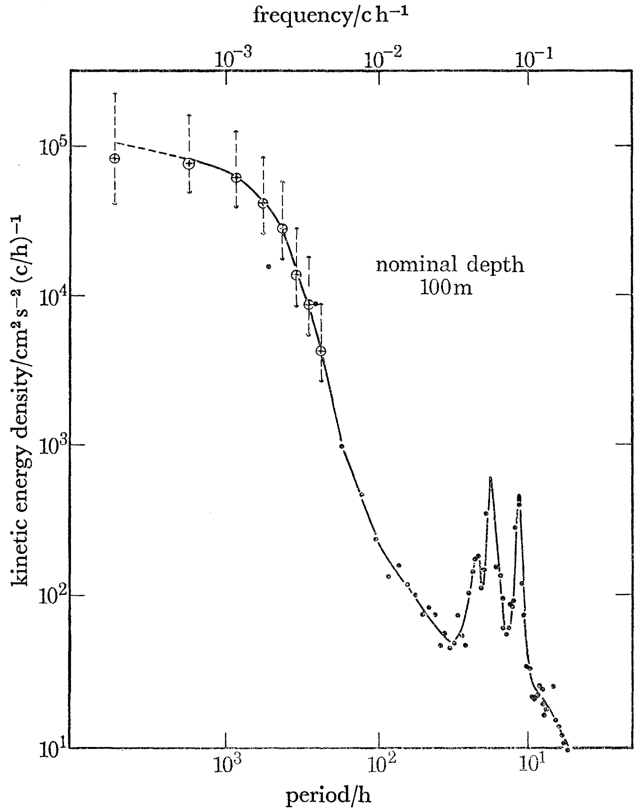

FIGURE 11. A spectrum of horizontal kinetic energy (from Thompson 1970). The kinetic energy density appears not to continue increasing at progressively lower frequencies. The dashed arrows are the approximate 80 % confidence intervals.

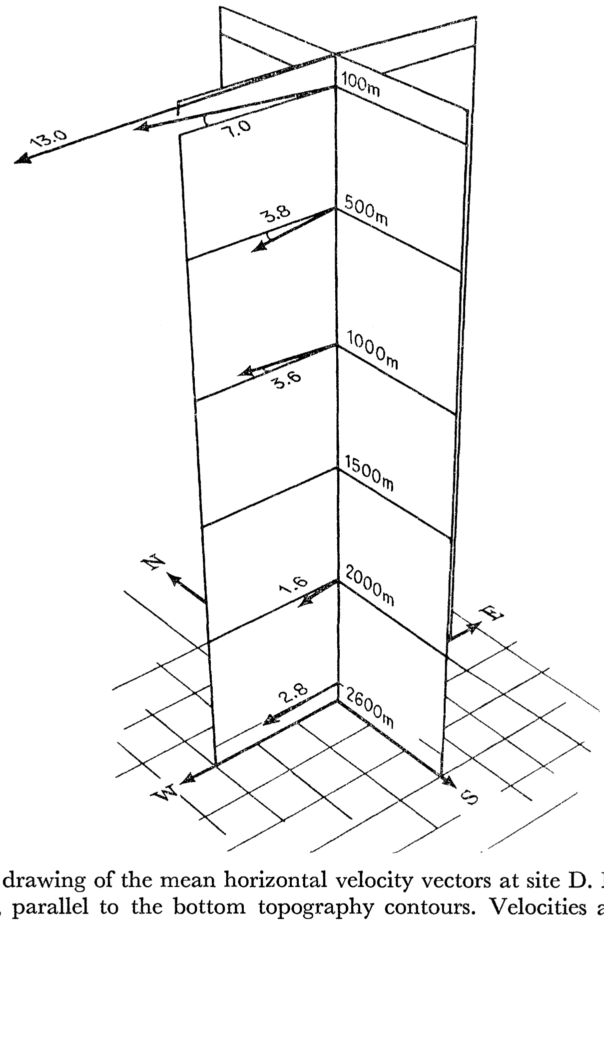

FIGURE 12. A perspective drawing of the mean horizontal velocity vectors at site D. Note that the mean vectors are nearly westward, parallel to the bottom topography contours. Velocities are in cm/s (modified from Webster 1969*a*).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

Mean properties and circulation

Averages of ocean currents taken over several years at site D show a systematic mean circulation. Measurements have been collected at a number of standard depths. At all depths the mean currents are to the west (figure 12) parallel to the isobaths of bottom topography in the region. The amplitude of the mean velocity shows a general decrease with depth at upper and mid depths, but increases near the sea floor.

The mean properties of the time-dependent currents can be examined independent of their direction or phase by examining kinetic energy. The kinetic energy of the time-dependent currents at site D is several times larger than the kinetic energy of the mean currents (table 1).

Table 1. Kinetic energy of mean and time-dependent currents at site D

depth	kinetic energy of mean	kinetic energy of fluctuations	ratio: fluctuations	total kinetic energy
m	$cm^2\,s^{-2}$	$cm^2\,s^{-2}$	mean	$cm^2\,s^{-2}$
10	85	404	5	489
100	25	197	8	222
500	7.0	34	5	41
1000	6.5	20	3	27
2000	1.2	16	13	17
2500	7.9	71	9	80

The mean value of total kinetic energy at a given depth at site D is remarkably similar to the corresponding value at other locations in the North Atlantic Ocean (Webster 1971). Neutrally buoyant (Swallow) float and current meter measurements of kinetic energy made by Swallow and Gould at N.I.O. have been compared with the site D values. Energies are generally within a factor of two of those at site D. A notable exception is the kinetic energy at 4000 m measured with floats in the Bermuda region by Swallow. The kinetic energy there is significantly greater than would be expected from an extrapolation of the site D kinetic energy profile. An explanation of the difference between the energy levels at great depths is needed. In addition, the short-term variations of kinetic energy are large and a study of them may help in the understanding of the dynamics of large-scale processes in the ocean.

The scientific programme reviewed here has been supported by the U.S. Office of Naval Research, currently under contract N000 14-66-CO 241. This is contribution 2614 from the Woods Hole Oceanographic Institution.

References (Fofonoff & Webster)

Berteaux, H. O. 1970 Design of deep-sea mooring lines. *Mar. Tech. Soc. J.* **4** (3), 33–46.
Fofonoff, N. P. 1966 Oscillation modes of a deep-sea mooring. *Geo-Marine Tech.* **2** (9), 13–17.
Fofonoff, N. P. 1968 Current measurements from moored buoys, 1959–1965. *Woods Hole Oceanogr. Inst. Ref.* 68–30 (unpublished manuscript).
Fofonoff, N. P. 1969 Spectral characteristics of internal waves in the ocean. *Deep Sea Res.* (Suppl. to **16**), 59–71.
Frankignoul, C. 1970 The effect of weak shear and rotation on internal waves. *Tellus* **22** (2), 194–204.
Perkins, H. T. 1970 Inertial oscillations in the Mediterranean. Ph.D. Thesis, Woods Hole Oceanog. Inst. and Mass. Inst. of Tech.
Pollard, R. T. 1970*a* On the generation by winds of inertial waves in the ocean. *Deep Sea Res.* **17** (4), 795–812.
Pollard, R. T. 1970*b* A compilation of moored wind and current meter observations. *Woods Hole Oceanogr. Inst. Ref.* 70–40 (unpublished manuscript).
Pollard, R. T. & Millard, R. C., Jr. 1970 Comparison between observed and simulated wind-generated inertial oscliations. *Deep Sea Res.* **17** (4), 813–821.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

Downloaded from rsta.royalsocietypublishing.org

Richardson, W. S., Stimson, P. B. & C. H. Wilkins 1963 Current measurements from moored buoys. *Deep Sea Res.* **10** (4), 369–388.

Schmitz, W. J., Jr., Robinson, A. R. & Fuglister, F. C. 1970 Bottom velocity observations directly under the Gulf Stream. *Science, N.Y.* **170** (2), 359–365.

Siedler, G. 1971 Vertical coherence of short-periodic current variations. *Deep Sea Res.* **18** (2), 179–191.

Thompson, R. 1971 Topographic Rossby waves at a site north of the Gulf Stream. *Deep Sea Res.* **18** (1), 1–19.

Voorhis, A. D. 1968 Measurement of vertical motion and the partition of energy in the New England slope water. *Deep Sea Res.* **15** (5), 599–608.

Webster, F. 1967 A scheme for sampling deep-sea currents from moored buoys. In *Trans. 2nd Int. Buoy Technology Symposium*, pp. 419–431. Marine Technology Society, Washington, D.C.

Webster, F. 1969*a* Vertical profiles of horizontal ocean currents. *Deep Sea Res.* **16** (1), 85–98.

Webster, F. 1969*b* Turbulence spectra in the ocean. *Deep Sea Res.* (Suppl. to **16**), 357–368.

Webster, F. 1971 On the intensity of horizontal ocean currents. *Deep Sea Res.* **18** (in the Press).

Webster, F. & N. P. Fofonoff 1965 A compilation of moored current meter observations, Volume I: *Woods Hole Oceanogr. Inst. Ref.* 65–44; 1966, Volume II: *Woods Hole Oceanogr. Inst. Ref.* 66–60; 1967, Volume III: *Woods Hole Oceanogr. Inst. Ref.* 67–66 (unpublished manuscripts).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES