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ABSTRACT

Current measurements collected from an array of moored buoy stations off the coast of Oregon from April through November 1969 have been used to study the spatial and temporal structure of oceanic currents over the continental slope in the northeastern part of the Pacific.

The typical spectra may be subdivided into low-frequency, intermediate-frequency, and high-frequency ranges. The variation in low-frequency motion (mean flow), the generation and decay of inertial-frequency motion, and the intensity of the high-frequency motion (turbulence) have been found to be related to the local atmospheric motion. The site of the observations and the configuration of the array of instruments used for this study have been found to be satisfactory for further study of the generalized mesoscale processes of the transfer of momentum from the atmosphere and of the oceanic response.

1. Introduction. What is the most typical spectral structure of oceanic motion? How does it change seasonally and geographically? How does the
change relate to the depth, temperature, salinity, and wind-stress distribution?

These are some of the representative questions confronting oceanographers who are today working on the variability in the oceanic environment and on the time-dependent motions in the sea. Direct and continuous measurements by a network of instrumented oceanographic buoys has become one of the most effective ways of studying oceanic motion and hopefully providing some answers to these questions.

The area under observation is a small region of the northeastern Pacific in the boundary zone near the Oregon Coast; the current regime here is highly variable and not well defined. The boundary zone further to the south is directly influenced by the California Current, whose oceanographic variability has been intensively studied, particularly in relation to its seasonal variation and its prominent upwelling.

A drift-bottle and drogue experiment (Burt and Wyatt 1964, Stevenson et al. 1969) has confirmed the existence of a reversible meridional current, which flows equatorward in the summer when the winds are northwesterly and poleward during the winter when the winds are southerly. Other efforts, mostly confined to the continental shelf area immediately adjacent to the coast, have confirmed the variable nature of oceanic motion (Collins and Pattullo 1970) and the fairly complex structures in the area (Collins et al. 1968). A more complete knowledge of this complex structure with its high degree of time dependency requires the deployment of an array of unmanned oceanographic platforms.

To investigate the typical characteristics of variable oceanic motion and their relationships to the mechanism of momentum transfer that is common to the northeastern Pacific, the oceanographic stations should be installed in deep water, away from the influence of the local coastal topography. Technological limitations, i.e., mainly the difficulty of maintaining a number of stations at
a water depth of 3000 m, restricted the initial phase of our experiments to water depths of 1000 m or less. The site selected for this study represents the necessary compromise, and it has proved to be ideal for the observation of the general processes of oceanic motion and momentum transfer over a wide frequency range. The following is a summary of our first observations.

2. Data Acquisition. An L-shaped array of three buoy stations has been moored over the continental slope approximately 50 km off the coast of Oregon where the bottom depth is between 700 m and 1000 m (Fig. 1). Braincon Model-381 Current Meters, placed at 40 m, 80 m, and 120 m below the surface, recorded the direct measurements of currents as time series of ten-minute means of speed and direction. These series were decomposed to $x$ (E–W) and $y$ (N–S) components, which were then analyzed through a modular time-series analysis subroutine system called ARAND-system (Ochs et al. 1970). Examples of the results of such analyses are given here.

The data, summarized in Fig. 2, were collected from April through November 1969. Because of instrument failures and installation difficulty, there are some gaps in the time series; these omissions indicate the importance of good technological support for this type of oceanographic experiment. Details of the data acquisition and of the reduction technique have been published (Gilbert et al. 1970).
3. Typical Spectra. An example of the spectral-density function, calculated from measured time series, is shown in Fig. 3. The general features associated with this example were common to all of the spectra calculated from the various segments of the time series. The distinct peak at the semidiurnal tidal frequency (S), the peak at the inertial frequency (I), and the less distinct but discernible peak at the diurnal tidal frequency (D) are always present. On the low-frequency side, there occur a few distinct crests, the magnitude and location (in frequency) of which vary from one spectra to another. On the high-frequency side, the spectral density decreases rather monotonically; it apparently follows a kind of power-law relationship except for the extreme high-frequency end. There is some difference between the spectra of the E–W and N–S components. The peak at S is always higher for E–W, sometimes exceeding that at the inertial period. At the longer periods (more than 5 days) the spectral density for N–S generally dominates that for E–W. Otherwise the spectral shape is almost identical for both E–W and N–S components.

In view of these features, the discussion that follows is subdivided into low-, intermediate-, and high-frequency ranges. These scale divisions are shown on Fig. 3.

4. Low-frequency Motion. The periodicity of this motion is of the order of weeks and months. Ideally, a set of continuous measurements over a period of more than a year should provide sufficient data for a statistical analysis that is suited to the motion of this frequency range. Because of the numerous gaps in our data (Fig. 2), it is not practical to do such an analysis. Therefore the fol-
lowing discussion is limited to those features revealed by the Integrated Velocity Diagrams (IVD) that have been constructed to facilitate an understanding of the low-frequency variation in the magnitude and in the direction of the oceanic motion. Examples are shown in Fig. 4.

In general, the current flows southward during May through July. From the latter part of July to mid-September there is a period of N–S stagnation. The current then starts flowing northward. During October the current frequently attains a speed of one knot, which is in general agreement with the temporal pattern already established for this region (Burt and Wyatt 1964, Collins and Pattullo 1970).

Fig. 4 reveals some additional features that may deserve further exploration. One is the association of the offshore flow with the southward current and of the onshore flow with the northward current. Again, this is in general agreement with our knowledge that upwelling occurs during late spring and early summer whereas downwelling occurs during fall and early winter. But this may be the first observation that the onshore-offshore transport has been associated with the north-south variation of flow over such a long period of time.

Another feature is the strong offshore transport during the period of N–S stagnation (August and early September), where the offshore transport exceeds at times a speed of 0.5 knot. This indicates fairly intense upwelling during the time when the N–S flow almost disappears. If we assume a uniform offshore flow of 20 cm/sec over the upper 100 m at St. 1, which corresponds to the vertical transport by upwelling for approximately 50 km between the station and the coast, the rate of upwelling should be $4 \times 10^{-2}$ cm/sec.

The offshore flow speed, when subjected to a low-pass filter, is shown in Fig. 5. The variation in the offshore transport rate, though large and frequent, is indicative of a long-term trend. The upwelling intensity reaches its maximum in early September, and the change to the onshore transport comes near the end of that month. September is certainly an interesting period for further investigation.

In September the eastward flow is associated with the northward-flowing current, which is a deviation from the normal pattern. It was in mid-September that a confined core region of extremely cold water was observed off Cape Blanco during an Oregon State University expedition (Wyatt, personal communication). It is not known whether this cold spot is a temporary and direct manifestation of the transition as revealed in the deviatory behavior of the IVD, and it deserves further study.

To what extent is this variation in the low-frequency current speed related to changes in the wind stress? Fig. 6 shows the vector averages for wind over five-day periods as recorded at Newport, Oregon, some 50 km east of the buoy stations. There is general agreement between the wind and the current relative to their onset, intensity, and termination, particularly during June through September. For May and October the relationships are not so well established.
Figure 4. Integrated current-velocity diagrams. Dates are given in italic numerals, with the month first, then the day.
Figure 5. Onshore-offshore components of velocity, low-pass filtered (cut-off frequency 0.0033 cycles per 10 min.). Data segments nos. 7, 8, 9, and 12.

Note that the cessation of southerly wind in the early part of October is followed by a weakening and cessation of northward flow at St. 1: at 80 m, a few days later, and at 120 m, a week later (see Fig. 4).

Figure 6. Wind velocity (vector average over five days) as measured at Newport, Oregon. Units in knots. * indicates no data available.
5. Intermediate-frequency Motion. As is shown in Fig. 3, the spectral configuration in the intermediate frequency is characterized by: a major peak at the semidiurnal tidal frequency (S) and at the inertial period (I), and a minor peak at the diurnal tidal frequency (D).

The inertial period at our stations is approximately 0.01 cycle/10 min. (or 0.06 cph). For the E–W component, the semidiurnal tide is the most prominent feature, followed by the inertial-period peak. For the N–S component the inertial-period peak often exceeds the semidiurnal peak. The magnitude is about the same for both E–W and N–S components at the inertial period.

In order to reveal the temporal features of both the inertial-period motion and the semidiurnal tide, Fig. 7 shows the result of complex demodulation at these two frequencies for both the E–W and N–S components. The temporal variation in amplitudes of the inertial-period motion is not related to that of the semidiurnal tide and is characterized by intermittency while the tide varied more slowly in amplitude. In another study, using the same current record, Sakou (1970) has shown that these inertial-period motions are well correlated with the local wind-stress variation and that the build-up and decay of the motion is accomplished over a relatively short period of time. The latter feature may account for the intermittency of the motion also. The phase relationship
Figure 8. Phase relationship for the inertial-period motion. Data segment No. 5.

Figure 9. An example of coherence and phase relationship between N–S and E–W components. Data segment No. 14. Coherence squared; phase in degrees; N–S leading E–W. Frequency in cycle per ten minutes.
between the E-W and N-S components of inertial-period motion indicates that the motion is clockwise (as it should be in the northern hemisphere), with the N-S component leading by approximately 90° (Fig. 8).

The cross-spectral calculation performed on the sets of N-S and E-W components of current velocity shows that the coherence for the inertial-period motion is always close to unity while that for the semidiurnal tide motion is rather small (Fig. 9). However, this apparent lack of coherence for the tide is due to our choice of the coordinate system; the coherence becomes nearly unity when the coordinate system is rotated by about 45°. In the case of the inertial-period motion, the rotation of the axis does not substantially influence the magnitude of coherence.

The spatial structure of these motions is of considerable interest. Webster (1968) concluded that the inertial-period motions are essentially transient phenomena of thin vertical extent and of narrow latitudinal extent. He found that the coherence at the inertial frequency is as high as 0.7 for stations separated by 3 km whereas the coherence is in the neighborhood of 0.2 for the sensors at the same location but with a vertical separation of less than 100 m.

Examples from our analyses are shown in Fig. 10. For the inertial-period motion, the result shown is in good agreement with Webster's findings. The coherence for a horizontal separation of more than 10 km (12–14) is much higher than that for a vertical separation of only 40 m (10–11). The coherence 7–10 is approximately equal to the product of the above two. In the case of the semidiurnal tides, the relationship is reversed, with a high coherence for the vertical separation and a low coherence for the horizontal separation. The influence of the local bottom topography may account for the latter feature, and the same relationship may not hold for the deep-sea motions.

There are other minor peaks of longer period. The longer-period peaks, however, change location and height from one data sample to another. A set of longer and better-coordinated measurements is absolutely necessary before the nature of these low-frequency motions can be defined.
6. High-frequency Motion. In the range of frequency between 0.017 cycle/10 min. and 0.17 cycle/10 min., the calculated spectra show almost entirely a consistent power-law relationship, which may be represented by $-5/3$ power. Webster (1969) first showed that the observed relationship agrees well with that established for the isotropic homogeneous turbulence, despite the fact that the basic hypothesis of isotropic and homogeneous turbulence does not obtain in the oceanic environment. Bye's (1970) work on the two-dimensional turbulence in the ocean, if extended to the interior of the ocean, would be of interest in this regard. The examples from our analyses are shown in Fig. 11 for the E–W and N–S components combined.

Fig. 9 shows that the coherence between these components is always insignificant, which is further evidence that the current in this frequency range is truly “turbulent”.

The relationship between the energy-density estimate of $f = 10^{-1}$ cycle/10 min. and the peak energy density at the inertial period, as estimated from some of the calculated spectral functions, is plotted in Fig. 12. The first value may be taken as an indirect measure of the inertial subrange. It is essential to know the Taylor velocity if the coefficient of energy dissipation is to be calculated.

Fig. 12 suggests that there is a positive correlation between the two quantities. It is not known whether this can be taken as an indication that the turbulent energy is fed by the energy stored in the form of inertial-period motion. Is it valid to hypothesize that the feature of the spectral function in this frequency range is due to turbulence? Recently there have been suggestions that the spectral features in this frequency range may be accounted for by the internal waves in the presence of weak shear (Fofonoff 1969, Frankiganoul 1970). Resolution of the problem requires a carefully planned experiment that employs an array of temperature and current sensors having dimensions smaller than those employed in the present experiment.
An elementary array of moored current-meter stations produces valuable sets of data for an investigation of temporal and spatial variation in oceanic currents. Such data, if combined with data from simultaneous continuous observations on marine atmospheric conditions, would make possible a study of the processes involved in the transfer of momentum between the atmosphere and the ocean over a broad range of frequencies.

Our study shows that the sites selected for the acquisition of data have been satisfactory for two reasons: (i) there is substantial intercorrelation between the local atmospheric motion and the response of the ocean, making it possible to interpret the result in terms of momentum transfer; (ii) the spectral features are more oceanic than coastal.

We have shown that the low-frequency flow of water responds rather quickly to the low-frequency change in wind stress, with the response being progressively retarded from the surface downward. The relatively rapid response makes this part of the ocean more attractive as a site for the study of mesoscale oceanic response to atmospheric excitation.

Buoy-station oceanography is expected to be most productive in the intermediate-frequency range. Our results have proved the validity of such expectation. The dominance of the intermediate-frequency range and its direct correlation with the local atmospheric motion of the inertial-period motion is the most significant feature observed. The spatial structure revealed in this study is consistent with the recent findings of other investigators. Our results indicate that the configuration and scale of the array of instruments have been satisfactory for this preliminary experiment; in order to perform more specific experiments, some adjustments would be necessary.

For a study of the generation of the inertial-period motion, a closer vertical spacing of the sensors near the water surface may be desirable. The position of the thermocline is of importance. A study of the decay of the inertial-period motion and a comparative investigation of the tides may require sensors in the deeper water. The horizontal spacing needs to be adjusted accordingly.
The high-frequency motion has demonstrated a systematic trend that invites further examination of its structure. This would require more extensive measurements than in this experiment.

Our study indicates the usefulness at this stage of the kind of experiment reported here. However, more advanced experiments should be so organized that they meet, step by step, a set of specific goals, thus producing the results that would be more meaningful. One possibility is to design separate experiments to fit each of the frequency ranges discussed above. With such a scheme, it might be possible to combine and coordinate diversified experiments in order to minimize redundancy and make the experiments economically feasible.

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REFERENCES

Burt, W. V., and Bruce Wyatt

Bye, J. A. T.


Collins, C. A., and June G. Pattullo

Fofonoff, N. P.

Frankiganoul, C. J.

Gilbert, Kathy, Asa Robinson, Toshitsugu Sakou, and Robert Still

Ochs, L. E., J. S. Baughman, and J. Ballance
1970. OS-3 ARAND System: Documentation and Examples, 1., Computer Center, Oregon State Univ.
SAKOU, TOSHITSUGU

STEVENVON, M. R., JUAN G. PATTULLO, and BRUCE WYATT

WEBSTER, F.