BENTHIC CURRENT OBSERVATIONS AT DOMES SITES A, B, AND C
IN THE TROPICAL NORTH PACIFIC OCEAN

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Abstract

Benthic current measurements are reported from three locations (A: 8°27'N, 150°49'W; B: 11°42'N, 138°24'W; C: 14°38'N, 125°29'W) in the eastern tropical Pacific. Near-bottom stratification was weak at all sites. The measurements were of 4- to 6-month duration. Mean currents were small and to the northwest; however, low frequency fluctuations dominated the records. These fluctuations had dominant periods for the meridional component of 2 months at all sites; the zonal component had periods varying from 2 months at the easternmost site to about 5 months at the other sites. Low frequency kinetic energy increased from west to east. Vertically, the low frequency motions were coherent over the bottom 200 m. A small speed increase was observed from 200 m to 30 m off the bottom; below this the speed decreased. Interpretation of these data in terms of an Ekman layer showed counterclockwise (looking down) veering between 30- to 6-m levels, which was consistent with the expected layer thickness of 25 m.

High frequency inertial-internal wave oscillations were also investigated. The inertial oscillations were intermittent and showed evidence for downward energy propagation. Mean energy level and lack of correlation between low frequency currents and internal wave energy suggests that the bottom topography is not a strong source of high frequency internal wave energy in our data.

*Contribution No. 398 from the NOAA/ERL Pacific Marine Environmental Laboratory.
Introduction

To the physical oceanographer, the abyssal ocean represents a largely unexplored and potentially important region. Mean currents in deep water result from the thermohaline general circulation modified by topography. Superposed on this flow, motions with a spectrum of frequencies provide large variability that can yield individual current measurements far greater than the mean. Observed water mass properties are the net result of advection and diffusion. The exchange processes that occur within the boundary layers adjacent to the surface, the continental margins, and the bottom modify the circulation and water characteristics of the interior of the ocean. Thus, the currents and stratification of the benthic boundary layer are of interest, as are their possible effects on the general circulation.

In this paper we report near-bottom measurements made at three sites in the eastern tropical Pacific Ocean. These data were collected as part of the Deep Ocean Mining Environmental Study (DOMES) program of NOAA. The physical oceanographic characteristics of this region were largely unknown; therefore, the experiment was designed to provide a preliminary description of the stratification and current fields. The presented analysis focuses on temporal scales of the currents, differences among the sites, and some investigation of potentially important internal wave processes.

Review

The study locations (Fig. 1) are in a region of abyssal hills between the Clarion and Clipperton Fracture Zones. A gradual slope to the east decreases the mean depth from site A (151°W) to site C (125°W) by about 500 m. Bathymetric charts (Chase et al., 1970) indicate a few nearby seamounts: 75 km east of A, a mount rises about 1000 m; 120 km east of C, a mount rises about 2000 m. However, in the immediate vicinity of the arrays, the relief is confined to vertical changes of about 200 m over a few kilometers horizontally.

Historical data of near-bottom currents in this area of the tropical Pacific are scarce. Most of the information on mean flow direction has been obtained from water mass analysis and theoretical models of abyssal circulation. Wong (1972) postulated an eastward bottom velocity south of Hawaii by tracing observations of anomalous values of oxygen, potential temperature, and salinity. This result agrees with near-bottom potential temperature distributions shown by Mantyla (1975) and with theoretical circulation models of Stommel and Arons (1960) and Kuo (1978). Superimposed on existing mean flow, one expects time-dependent fluctuations with frequencies ranging up to the local Brunt-Vaisälä frequency (about 0.2 cph). Low frequency (less than inertial frequency) mesoscale eddies presumably contribute a significant fraction of the total variance. Wyrtki et al. (1976) produced maps of near-surface
eddy kinetic energy per unit mass for the world oceans. These maps indicated an increased energy in the north equatorial region. Within our study area, surface eddy kinetic energy increased by more than a factor of 2 proceeding from 15°N to 8°N. It is not known whether these surface features are associated with a deep eddy structure. Direct current measurements of sufficient length to resolve the mean or low frequency currents do not exist for this region. Near the eastern site (C) Amos et al. (1976) reported 1-month measurements of near-bottom currents. Two other long-term deep-current measurements have also been reported in the tropical Pacific; Taft et al. (1974) report a 4.5-month record from 1°S, 150°W, and Harvey and Patzert (1976) report 2-month records from about (0°, 95°W). We will compare these data to our results.
Information on the characteristics of the benthic boundary layer that have been obtained in other locations may be pertinent to the tropical Pacific. Continuous vertical profiles of potential temperature, salinity, and density that show an apparently well-mixed layer adjacent to the bottom have been presented for many oceanic locations. Amos et al. (1971) discussed such layers near the Blake-Bahama Outer Ridge in the Atlantic Ocean. Biscaye and Eittreim (1974) and Eittreim et al. (1975) studied suspended particulate matter and excess radon profiles taken over the Blake-Bahama Outer Ridge and over the Hatteras Abyssal Plain; the lack of near-bottom stratification in these parameters as well as in potential temperature indicates active mixing. In the Hatteras Abyssal Plain and to the east (55°W), Armi and Millard (1976) and Armi (1978) have found bottom layers thicker than 50 m. These studies in regions of weak mean flow, which are remote from large topographic features, might be expected to be similar to the tropical Pacific. The dynamics of the bottom mixed layers have been investigated by several authors (Wimbush and Munk, 1971; Weatherly, 1972, 1975; Thompson, 1973; Csanady, 1974; Armi and Millard, 1976). In general, some form of a modified Ekman boundary layer is assumed. The presence of topographic gradients and time-dependent velocities complicates the interpretation. Armi and Millard (1976) were able to correlate the mixed-layer thickness with low frequency near-bottom velocity. Such a relation would be expected if Ekman dynamics held; however, the thickness observed over a flat bottom was six times greater than the turbulent Ekman layer thickness.

Coupling between mixing and low frequency flow can effect the dynamics of mesoscale circulation. In addition, topography-current interaction can modify the flow found within a few kilometers of the bottom. Results from the Mid-Ocean Dynamics Experiment (MODE-I Dynamics Group, 1975) and subsequent current measurements in the North Atlantic (Schmitz, 1978) show effects that may be related to bottom topography. In MODE, the structure of mesoscale eddies with periods longer than the inertial period were studied. Near bottom these eddy motions had smaller time scales and larger horizontal kinetic energy than they did at mid-depths (1500 m). The spatial scales were also contracted near bottom, and localized currents were observed near some major topography. Rhines (1977) interpreted the general MODE results in terms of topographic influences on baroclinic Rossby waves. This picture of energetic, small-scale benthic currents, which data and theory suggest, contrasts with the intuitive notion of a sluggish, homogeneous abyssal flow.

In addition to modifying mesoscale currents, the bottom topography may have a dominant influence on energy dissipation. Rhines (1977) points out that a search for energy sinks that dissipate mesoscale eddies is critical. Conventional drag laws indicate that over a smooth bottom friction can contribute only a small amount. However, Bell (1975) investigated the generation of internal waves by the interaction of low frequency deep ocean currents with bottom topography. Using abyssal hills and a velocity amplitude of 5 cm/s
for the low frequency currents as an example, he found an internal wave drag equivalent to about 0.5 dyn/cm². This production mechanism could contribute a significant fraction of the internal wave energy observed in the ocean. Few observational tests of Bell's conclusions have been made. In a study of several deep current meter records in the North Atlantic, Wunsch (1976) observed that the most significant internal wave inhomogeneity observed was associated with a seamount. Thus, bottom topography may be a source; however, its relative importance has not been established.

Description of the Experiment

Figure 1 gives the locations of our moored array measurements. At each site, a single mooring was deployed with current meters at 6 m, 30 m, 50 m, and (at C) 200 m above the bottom. Deployments were from May to November 1976 at A and B and from July to December 1977 at C. The detailed bathymetry at each location derived from local ship surveys represents our best estimate of the mooring location. Both A and B appear to be part-way up a small hill, while C is in a long valley. The local gradients (maximum ~.05) shown in these figures are typical of the area around the arrays.

Current meters used were vector averaging current meters (VACM) manufactured by AMF Electrical Products Division, Alexandria, Virginia. These instruments sense speed with a Savonius rotor (16-cm diameter), direction with a vane (17 cm), and temperature with a bead thermistor. As the rotor turns, the instrument internally resolves east-west and north-south velocity components and stores the data on magnetic tape. The effective threshold is about 2 cm/s (McCullough, 1975). Individual rotor and vane calibrations which we made in a tow tank showed variation in this threshold; however, most instruments followed a standard calibration curve (given in Halpern et al., 1974) for speeds higher than 2 cm/s. In the data discussed here, instruments recorded every 15 minutes. During processing, any 15-min interval with an indicated speed less than 2 cm/s was assigned speed and direction of zero. This procedure probably underestimates mean currents. Threshold problems were most severe at A, where over 50% of the recorded values were below threshold and periods of several days contained no measurements above 2 cm/s. At the other two locations, the records do not appear to be seriously contaminated by the instrument thresholds; however, during periods of weak low frequency currents, estimates of internal wave energy may be erroneous.

The current-meter temperature sensors were calibrated as described in Halpern et al. (1974). Absolute temperature calibration had an expected error of ±.01°C; relative temperature changes were sensed with a resolution better than .001°C. In view of the weak near-bottom temperature stratification, the temperature measurements were not accurate enough to establish gradients; however, temperature changes at each level were resolved.
In addition to moored arrays, continuous profiles of conductivity, temperature, and depth (CTD) were taken with a Neil Brown Instrument System Mark III CTD. These profiles were processed as described in Fofonoff et al. (1974) in order to obtain temperature and salinity profiles. During the November 1976 deployment cruise, detailed studies were made in the vicinity of A and B. Unfortunately, subsequent processing revealed two problems with the CTD system: a) temperature-dependent noise level in the temperature measurements, which at cold temperatures yielded a noise level about ten times that expected from the instrument quantizing increment (0.0005°C); and b) temperature instabilities of a few millidegrees. The first problem was traced to a component in the temperature-sensing electronics; the second problem may be related to a high pressure leak caused by a manufacturer’s defect in the conductivity cell. In any case, these relatively small temperature errors made precise near-bottom profiles impossible. These problems were corrected prior to the site C CTD measurements that were made in July 1977. Also, site A was reoccupied in March 1978; these data are presented here on the assumption that the near-bottom water mass structures are reasonably constant.

Figure 2 shows representative profiles of potential temperature (°) at each location. Polynomials developed by Bryden (1973) were used to calculate θ. Bottom potential temperature increased to the east (0.98°C at A, 1.03°C at B, and 1.09°C at C) in agreement with the historical data (Wong, 1972; Mantyla, 1975). Potential temperature gradient decreased at the bottom. Over the lowest 200 m, this gradient was about 2 x 10^-3°C/m. This value is one order of magnitude less than the background stratification observed by Armi and Millard (1976) over the Hatteras Abyssal Plain. The weak mean gradients may account for the lack of an obvious bottom mixed layer in our data; the layer would have to exceed 50 m in thickness in order to be measureable.

Potential temperature-salinity diagrams for the abyssal water at sites A and C are shown in Fig. 3. These diagrams show the linear θ-S relation for the deep Pacific; note that due to water depth differences, the site-C curve is essentially a continuation of the site-A curve at higher temperatures. No distinct near-bottom water mass is seen.

**Velocity and Temperature Time Series**

Time series of velocity and temperature are shown in Fig. 4. The visual impression of these records is similar at all sites. Low frequency oscillations with periods of several weeks were superimposed on the high frequency inertial and tidal signal. The currents were vertically coherent. At site A, as mentioned above, extended periods (e.g., early September) of low current occurred, during which the speeds were below threshold. At site B, only the
Fig. 2. Benthic potential temperature versus depth profiles near each mooring. Note scale change at each site.

30-m current meter worked throughout the deployment. Low frequency structure here was quite pronounced with a rapid direction change observed in mid-July. Site C had the most complete data set with velocity measurements up to 200 m above the bottom. The vertical coherence of much of the structure over this depth interval is obvious. Also, non-stationarity in the high frequency signals was pronounced. Near the beginning of October, large oscillations are evident. Later analysis showed that these signals have frequencies near the inertial.

Because of nearly uniform bottom-water temperature and relatively large errors in absolute calibration (±0.01°C), temperature time series from the current meters are plotted in Fig. 4 relative
Fig. 3. Benthic potential temperature versus salinity diagrams for sites A and C. The structure in the bottom few hundred meters varied between casts so that the small salinity increase (0.002 ppt) seen at A is not considered significant.

to an arbitrary zero. Temperature changes at each site appeared vertically coherent. Site A had the smallest temperature variance over the record. This observation is consistent with the weak mean temperature gradients found in CTD data and the relatively weak currents at this location. At B, bottom temperature increased over the deployment period. Most of this increase occurred after the current change in mid-July; the warming probably represented lateral advection. The site B and C records show more visual correlation.

Fig. 4a. Hourly time series of currents and temperature at locations A and B. The origin for the currents is indicated by the horizontal line at each depth; the bar scale gives the speed. Temperatures are plotted relative to an arbitrary origin and only temperature changes are significant. Values in meters are heights above bottom.
DOMES BENTHIC CURRENTS

A: 8°27' N, 150°49' W

NORTH

TEMPERATURE

MAY JUN JUL AUG SEP OCT 1976

B: 11°42' N, 138°24' W

NORTH

TEMPERATURE

MAY JUN JUL AUG SEP OCT NOV 1976

Fig. 4a
Fig. 4b. Hourly time series of currents and temperature at site C. Same plotting convention as Fig. 4a.
between temperature and velocity than the record at A. In particular, at C both low and high frequency changes appear related. For example, the initial low frequency velocity change from northeast to southwest currents is accompanied by a decrease in bottom temperature. In addition, a sharp drop in temperature on about 1 October appears to accompany the onset of high frequency oscillations mentioned above.

The separation between low frequency and inertial-internal wave energy regimes can be seen clearly in horizontal kinetic energy spectra. Figure 5 shows variance preserving (area under the curve is proportional to the variance) spectra for the 30-m record at each location. Inertial frequencies at A, B, and C are \( f_A = 0.012 \) cph, \( f_B = 0.017 \) cph, and \( f_C = 0.021 \) cph. Note that the energy scales are different for each site. These spectra show characteristic structures similar to most deep-ocean data sets. There is high energy in the tidal and near-inertial frequency bands, a low energy region (spectral gap) for frequencies between inertial and about 0.05 cph, and a low frequency rise in energy below the gap. Most of the total variance in a long current record comes from the low frequency motions. The existence of the spectral gap facilitates filtering the time series into a low frequency sub-inertial time series and a high frequency inertial-internal wave time series. The relative amplitudes of the two components are shown graphically in Fig. 6, where low- and high-pass filtered series of the north-south component of velocity at site C (200-m level) are plotted. Clearly, instantaneous current measurements will have significant contributions from both spectral regions, and any attempt to study the characteristics of a region must resolve the low frequency flow.

**Low Frequency Motions**

To describe motions with frequencies less than the inertial frequency, the time series were filtered with a symmetric Gaussian filter (Schmitz, 1976). The filter width was chosen so that at each site the half-power frequency was one-half the inertial frequency. Fig. 7 is a plot of the data at all locations in vector form. The length of each stick represents current speed and the angle indicates direction. Both A and C exhibit high vertical coherence.

The relative importance of low frequency oscillations compared to the mean flow (averaged over the record length) is seen in Fig. 7 or Table 1. In the latter, \( KE = \frac{1}{2}(u^2 + v^2) \) where a bar over the velocities indicates record length averages. \( KE \) is the kinetic energy (per unit mass) of the mean flow. Primed velocities are defined as the standard deviation of the low-pass filtered data, again computed over the record length. \( KE', \) kinetic energy (per unit mass) of the low frequency flow, is given by \( KE' = \frac{1}{2}(u'^2 + v'^2) \).
Fig. 5. Horizontal kinetic energy spectra for the records 30 m above the bottom at each site. Spectra have been normalized so that the area under the curve is equal to the variance. Energy peaks at the semidiurnal frequency, inertial frequency \( f_A = 0.012 \text{ cph}, f_B = 0.017 \text{ cph}, f_C = 0.021 \text{ cph} \) and in the low frequency region are seen. Note changes in energy scale between sites.
Fig. 6. Meridional velocity component at the 200-m level of site C, showing the contribution of low frequency (Gaussian low-pass filtered time series as described in text) and inertial-internal wave band oscillations.

The double-primed energy relates to internal wave contributions and is defined as one-half of the difference between the total variance and the low frequency variance. Table 1 shows that KE' is, on the average, about ten times larger than KE. Mean velocity at all sites was to the northwest; however, the record lengths are insufficient for these mean velocities to be statistically significant. Interestingly, near-bottom currents appear somewhat larger than the currents above. At site C, mean speed increased by a factor of 3 between 200 m and 6 m. The low frequency speed increased between 200 m and 30 m, then decreased from 30 m to 6 m. KE' (6 m) roughly equals KE' (200 m) and is about 80% of KE' (30 m). North-south velocity differences [(v(200) - v(30))] are shown in Fig. 8 along with the velocity at 200 m. The southward mean velocity difference indicates that the 200 m northward velocity is smaller than the 30 m northward velocity. This difference reflects the baroclinic nature of the low frequency flow, rather than a constant bottom current. When the 200-m velocity is large, the shear is large; when the 200-m velocity is near zero, the shear is also small.

The time scale of the low frequency motion is obtained from autocorrelation functions of each velocity component (Fig. 9). These functions have an interesting pattern. At all locations the v component has a first zero crossing at about 15 days (corresponding to a dominant period of 60 days); the u component at sites A and B has a much longer time scale. For example, at site B, the zero crossing indicates a dominant period of order 180 days, which is essentially the record length. At site C, the time scales of u and v are almost equal. This same information is shown in spectral form in Fig. 10. Note that the energy scales differ at each location. All sites have a variance peak in the v component.
Fig. 7. Low-pass filtered velocity at all sites. Length of the sticks are proportional to speed and orientation of stick indicates direction.
<table>
<thead>
<tr>
<th>Location</th>
<th>Height Above Bottom (m)</th>
<th>Record Length (days)</th>
<th>$\bar{u}$</th>
<th>$\bar{v}$</th>
<th>$u'$</th>
<th>$v'$</th>
<th>$KE$</th>
<th>$KE'$</th>
<th>$KE''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A 8°27'N 150°49.1'W</td>
<td>50</td>
<td>143</td>
<td>-.29</td>
<td>.19</td>
<td>1.38</td>
<td>1.54</td>
<td>.1</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Site B 11°42'N 138°24'W</td>
<td>30</td>
<td>197</td>
<td>-1.68</td>
<td>1.37</td>
<td>3.38</td>
<td>3.29</td>
<td>2.4</td>
<td>11.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Site C 14°38'N 125°29'W</td>
<td>200</td>
<td>156</td>
<td>-.11</td>
<td>.59</td>
<td>1.54</td>
<td>3.66</td>
<td>.2</td>
<td>7.9</td>
<td>3.3</td>
</tr>
<tr>
<td>Site C 14°38'N 125°29'W</td>
<td>50</td>
<td>156</td>
<td>-.46</td>
<td>1.61</td>
<td>1.93</td>
<td>3.98</td>
<td>1.4</td>
<td>9.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Site C 14°38'N 125°29'W</td>
<td>30</td>
<td>156</td>
<td>-.62</td>
<td>1.79</td>
<td>1.82</td>
<td>4.17</td>
<td>1.8</td>
<td>10.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Site C 14°38'N 125°29'W</td>
<td>6</td>
<td>156</td>
<td>-.81</td>
<td>1.83</td>
<td>1.97</td>
<td>3.43</td>
<td>2.0</td>
<td>7.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Bars indicate averages over record length. Primes indicate low-pass filtered currents. The kinetic energy ($KE$) per unit mass is defined in the text.
Fig. 8. Low-pass filtered meridional velocity at 200-m level at site C (solid) and velocity difference between 200-m and 30-m level (dashed). Note when difference is negative northward component at 30 m exceeds component at 200 m.

at about .0007-.001 cph (periods of 42 to 60 days). In this spectral region, north-south oscillations dominate east-west motions. At lower frequencies the north-south energy decreases, while at A and B, the east-west energy continually increases (a red spectrum). At site C the u component variance is flat throughout the low frequency region. It should be mentioned that prior to calculating the Fourier transform, these records were detrended by joining the end points (Frankignoul, 1974a). This detrending reduces the contamination of the spectra by oscillations with periods longer than the record length.

Table 1 shows that the eddy kinetic energy $KE'$ increases from A to C. At the only common depth (30 m), B and C have essentially the same eddy kinetic energy, whereas A is lower by a factor of 5. The record lengths are too short, when compared to the dominant periods of the motion, to attach statistical significance to this energy increase. In the frequency band of the variance peak in meridional velocity (0.0005-.001 cph), the site C north-south spectral level exceeds that at site A by a factor of 7. This difference is significant at the 95% level. A small increase in meridional energy level (30%) from B to C is not statistically significant.

The observed current statistics can be compared with other measurements in this area, in the central Pacific, and in the North Atlantic. Amos et al. (1976) reported preliminary data from a 33-day record of near-bottom currents near C. At 20 m (200 m) they found mean velocities $u = -3$ cm/s (-2.3 cm/s), $v = .5$ cm/s (0 cm/s). Inspection of Fig. 4 shows that 1-month periods with similar mean speeds could be found. The dominance of western flow is in agreement with our records; however, the small north-south velocity is somewhat anomalous. It is encouraging to note that the near-bottom speeds increased in agreement with our observations. Amos' measurements were about 80 km away from our C array, so the bottom inten-
Fig. 9. Autocorrelation functions of low-pass filtered velocity components at 30-m level at each site.
Fig. 10. Variance preserving spectra of zonal (u) and meridional (v) velocity components at 30-m level. Note that the energy scale changes between sites. The low frequency peak seen at B and C is almost exclusively in the meridional component.
sification is probably not a local orographic effect.

In the equatorial Pacific at 0°30'S, 95°W, Harvey and Patzert (1976) reported measurements 10 m above bottom at two sites separated by 110 km. The low frequency structures were coherent over this separation and showed an oscillation with a period of about 25 days that was propagating westward. These data were interpreted as a first-mode baroclinic Rossby wave trapped at the equator. Further west, Taft et al. (1974) reported measurements at 1°02'S, 149°51'W (approximately 1000 km south of our site A) at 1500 m above the bottom. The mean flow was predominantly eastward throughout the record; however, the north-south velocity component had more low frequency variance. A prominent feature of the record was a meridional oscillation with a period greater than 2 months.

In the central Pacific, Ramp (1976) reports measurements made near 30°N, 158°W for a 9-month period. His data were from current meters 100 m off bottom at three sites where the water depth was about 5900 m. Eddy kinetic energy averaged over the three sites was 2.5 erg/cm³. This energy was divided equally between u and v components. These observations are similar to our site A measurement. In Ramp's data, zonal and meridional time scales determined from autocorrelation functions were approximately equal. They indicate dominant periods of 135-145 days. The shorter meridional time scale found for the tropical Pacific does not appear to occur further north.

Measurements during the Mid-Ocean Dynamics Experiment (MODE) and subsequent experiments (POLYMODE) in the North Atlantic represent a much more detailed study of low frequency motions than the results presented here. However, our preliminary survey can be compared with some results of MODE. For example, both bottom intensification and meridional dominance in the deep water were part of the MODE results (MODE Group, 1978). Currents were not measured close to the bottom during MODE; the intensification was observed from 1500-m to 4000-m depth and may not be related to the feature we see. The ratio of meridional to zonal variance was about 1.6 at 4000 m at the MODE central site (MODE Dynamics Group, 1975). In our data this ratio varied from 1.5 at site A to 4.2 at site C. Considering the uncertainties in the low frequency kinetic energy determination, Atlantic and Pacific measurements are similar. The mean low frequency kinetic energy (KE') determined at our three sites can also be compared with the North Atlantic observations. Again, record length precludes a quantitative comparison; but the Pacific level is of the same order of magnitude as the values measured near the MODE site. These values are one order of magnitude smaller than the eddy kinetic energy seen near the Gulf Stream (Schmitz, 1976).
Inertial-Internal Wave Variability

In Table 1, KE" represents the horizontal kinetic energy contribution of frequencies higher than the local inertial frequency. In general, this high frequency kinetic energy was less than KE'. From the spectra in Fig. 5, most variance in the high frequency band comes from near-inertial and semidiurnal tidal oscillations. Small peaks at the diurnal period and near 6 hr are also seen. The latter is presumably associated with a tidal harmonic. Component spectra in Fig. 10 indicate that at site A the semidiurnal tide is predominantly east-west, whereas at sites B and C tidal motions are aligned meridionally. This result is substantiated by principal axes calculations (Gonella, 1972; Mooers, 1973) which show statistically significant orientations of 83°, 5°, and 14° at sites A, B, and C respectively. Although local topographic effects may be responsible for this anisotropy, the results at site C agree with measurements by Amos et al. (1976) which were 80 km away.

Our description of the inertial-internal wave band will focus on the nonstationarity of these signals and the possibility of near-bottom internal wave production. Deep-ocean measurements often show nonstationary inertial energy (e.g. Webster, 1968; Halpern, 1974). Near the surface these pulses of inertial energy can often be correlated with wind events (Pollard and Millard, 1970; Halpern, 1974); at deeper levels several measurements (Frankignoul, 1974b; Leaman and Sanford, 1975) indicate downward propagation. Near-bottom inertial currents could be caused by this downward propagation coupled with possible bottom reflection. On the other hand, inertial energy could be generated by the time-varying low frequency flow interacting with bottom topography. If near-bottom Ekman layers are important, then bottom generation of inertial oscillations might be similar to surface generation.

To study nonstationarity, the unfiltered data record was broken into pieces that were approximately two inertial periods long. These pieces were Fourier-transformed after detrending by joining the end points (Frankignoul, 1974a). To improve time resolution and to uncover spurious peaks, the Fourier analysis was repeated with the pieces shifted by one inertial period (i.e., half of the piece length). Time series of the energy in each of several bands were then constructed from the piecewise spectra. The inertial and semidiurnal bands consisted of one periodogram point each. Internal wave bands centered at periods of 10 hr and 5 hr were formed by frequency-averaging over 5 and 6 periodogram estimates respectively. Figure 11 is a plot of these horizontal kinetic energy time series as well as the horizontal kinetic energy associated with the low frequency flow for the 50-m level at site C. Note the relatively distinct structure seen in the inertial band about mid-October. This peak rises by almost a factor of 5 above the average level. This particular event was mentioned earlier since it is quite distinct in the time series plots (Fig. 4). The vertical
Fig. 11. Time series of horizontal kinetic energy (arbitrary units) in five frequency bands at site C (30-m level). The method of calculation is discussed in the text. Note the low visual correlation between bands and the large inertial energy burst seen in mid-October.
energy distribution is seen in Fig. 12. The event appears first at 200 m above bottom and then at 50-, 30-, and 6-m levels. No time delay can be discerned between the lower three levels (time resolution is about 2 days). The energy within the peak decreases toward the bottom. Based on these time series, it appears that the energy flux is downward from the upper waters rather than upward from the bottom. The observed delay of about 4 days between 200 m and 50 m corresponds to an energy propagation speed of about .04 cm/s.

The large time step (1 day) used in these calculations contributes to the uncertainty of this group velocity estimate. Mid-ocean observations by Frankignoul (1974b) in the central North Atlantic suggested a downward propagation speed of 0.5 cm/s—considerably faster than that observed here. Kroll (1975) pointed out that the propagation velocity depends on the frequency of the wave packet, the wavelengths of the oscillations, and the local stratification. In addition, he showed that the horizontal propagation velocity was generally much greater than the vertical propagation velocity; so that, for waves of a constant frequency, the rays travel about 100 km horizontally for each 1 km downward. Thus, the source of near-bottom inertial waves may be quite distant from the site where they are observed.

The second problem which we addressed in our study of the high frequency currents is the possibility of near-bottom internal wave generation. Such generation is related to low frequency currents interacting with near-bottom topography; thus, one expects a correlation between internal wave energy and low frequency energy. Figure 11 shows time series of low frequency, inertial, semidiurnal, and internal wave energy. No significant cross-correlation was found between internal wave energy and any lower frequency band. In addition, the mean energy level in the 10-hr internal wave band was within a factor of 2 of the energy level predicted by the Garrett and Munk (1975) internal wave model. This model describes mid-ocean internal waves in regions that are remote from energy sources or sinks. Our measurements, therefore, indicate no evidence for near-bottom production of internal waves.

The Bottom Boundary Layer

The velocity time series were examined to determine whether these data offered evidence of a near-bottom Ekman-like layer. In particular, most theories with turbulent Ekman-like dynamics (e.g. Weatherly, 1972, and references therein) predict a decrease in speed approaching the bottom and an angular veering counterclockwise looking down. Several techniques for estimating the veering are possible (Kundu, 1976); the most important consideration is to avoid instrumental effects in determining angular differences. The VACM has an angular resolution of 2.8°. However, at low speeds the vane direction is erratic. To eliminate this source of error,
Fig. 12. Inertial energy time series at site C for all levels. Energy scale (arbitrary units) is the same for all plots; origin for successive levels is offset by 2 units. Time lags indicate that the energy burst in October appeared first at the 200-m level.
we selected periods when the low-pass filtered velocity exceeded 3 cm/s. The analysis was only applied to the site C data, since this record was the most complete. Four periods with speeds above our criterion occurred: 7-25 July; 23 September-8 October; 31 October-10 November; 18 November-5 December. Combined, these periods total 64 days. Daily values of speed and direction were found by sub-sampling the low-pass filtered data at each depth. Table 2 summarizes the results; angles are given relative to true north. In the first three intervals, the mean speed increased from 200 m to 30 m and then decreased to 6 m. In these cases, the direction change from 200 m to 30 m was negligible; but from 30 m to 6 m a change of 7° to 10° counterclockwise was recorded. In the last interval, speed consistently decreased from 200 m to 6 m; however, above 30 m the direction changed in a clockwise sense, whereas from 30 m to 6 m the change was counterclockwise. Average veering from 30 m to 6 m was 9° ±2°; average sheer was 0.8 ±0.2 cm/s.

These results indicate that the current meters at 50 m and 200 m above bottom were above the influence of an Ekman layer; the 6-m level appears to be in the layer. An accurate estimate of the boundary layer thickness is not possible because of inadequate vertical resolution.

Theoretical calculations of boundary-layer thickness are probably not applicable in regions with topographic variations as large as those observed in this region. However, for lack of a better indicator, the expected thickness of a turbulent Ekman layer over a flat bottom in unstratified water can be calculated. In accordance with Armi and Millard (1976), the height of a turbulent Ekman layer $h_e$ is

$$h_e = 0.4 u_*/f$$

(1)

This relation is derived from the experiments of Caldwell et al. (1972) and Howroyd and Slawson (1975). The local inertial frequency is $f$; $u_*$ is the friction velocity at the bottom. For a smooth bottom, this velocity is given by Csanady (1967) as

$$u_* = 1/30 u$$

(2)

where $u$ is the velocity outside the boundary layer. Then, combining (1) and (2) and considering $u$ to be the mean speed at 30-m level (7 cm/s) during the four intervals considered gives

$$h_e = 25 m.$$  

(3)

The measurements are consistent with an Ekman-like behavior confined to a 25-m thick boundary layer. The turning observed is similar to that measured on continental shelves; Weatherly (1972) found a mean veering 10° under the Florida current, and Kundu (1976) found a veering of 6° off the Oregon coast.
TABLE 2  
Average speed and direction at site C for time periods indicated

<table>
<thead>
<tr>
<th>Time Period</th>
<th>200 m</th>
<th></th>
<th>50 m</th>
<th></th>
<th>30 m</th>
<th></th>
<th>6 m</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S</td>
<td>θ</td>
<td>S</td>
<td>θ</td>
<td>S</td>
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<td>θ</td>
</tr>
<tr>
<td>7 July-25 July</td>
<td>6.1 cm/s</td>
<td>343°</td>
<td>8.3 cm/s</td>
<td>340°</td>
<td>8.8 cm/s</td>
<td>339°</td>
<td>7.9 cm/s</td>
<td>328°</td>
</tr>
<tr>
<td>23 September-8 October</td>
<td>4.5 cm/s</td>
<td>331°</td>
<td>6.8 cm/s</td>
<td>329°</td>
<td>7.0 cm/s</td>
<td>331°</td>
<td>6.2 cm/s</td>
<td>324°</td>
</tr>
<tr>
<td>31 October-10 November</td>
<td>4.1 cm/s</td>
<td>347°</td>
<td>5.1 cm/s</td>
<td>347°</td>
<td>5.7 cm/s</td>
<td>348°</td>
<td>5.2 cm/s</td>
<td>341°</td>
</tr>
<tr>
<td>18 November-5 December</td>
<td>6.3 cm/s</td>
<td>163°</td>
<td>5.5 cm/s</td>
<td>165°</td>
<td>5.5 cm/s</td>
<td>170°</td>
<td>4.5 cm/s</td>
<td>160°</td>
</tr>
</tbody>
</table>

Periods selected had low-pass filtered velocity greater than 3 cm/s at all depths. Directions given with respect to true north.
Summary and Conclusions

Benthic current measurements have been described at three sites in the eastern tropical Pacific Ocean. Vertical stratification in this region was weak and the potential temperature-salinity relation was fairly uniform. Mean currents over the record lengths (4-6 months) were small and to the northwest at all sites. These mean velocities were not statistically significant because of large, low frequency (less than inertial) variance. These low frequency fluctuations contributed 50-80% of the total variance. Time scales and horizontal kinetic energy (per unit mass) varied among the sites. At all locations the meridional velocity component had an integral time scale of about 15 days (60-day period). At the eastern site (C), the zonal velocity time scale was similar; however, at A and B east-west oscillations had a dominant period nearly equal to the record length. Low frequency horizontal kinetic energy increased from west to east by a factor of 5. Vertical coherence on each mooring was large. However, between 200 m and 30 m both mean speed and amplitude of the low frequency oscillations increased. Below 30 m the speed decreased. Measurements of longer duration and greater vertical extent are required to relate the low frequency oscillations to the large-scale circulation of the tropical Pacific; however, our measurements point out the importance and some major characteristics of these motions.

High frequency oscillations contributed 20-50% of the total variance. Inertial and tidal motions were most important. Inertial oscillations were intermittent with brief periods where the energy in this frequency band exceeded the background level by one order of magnitude. These bursts of inertial energy were observed to propagate downward, and some evidence for near-surface generation was found. Energy in the high frequency internal wave bands was fairly uniform in time and had a gradual decrease toward the bottom. No correlation between internal wave energy and low frequency currents was found. Also, the mean energy level was within a factor of 2 of the "universal" spectrum for mid-ocean internal waves described by Garrett and Munk (1975). These observations suggest that over abyssal hills such as those that occur in the tropical Pacific, bottom topography is not a strong source of internal wave energy.

In the final section of this study, we compared bottom current measurements with theoretical ideas on Ekman boundary layers. Current veering between 30 m and 6 m was about 9° in the correct sense for an Ekman layer. Rough calculations indicated an expected layer thickness of 25 m, in agreement with observation. Our measurements did not show the very thick (about 6 h_e) bottom layers reported by Armi and Millard (1976) in the Atlantic.

This description of abyssal currents in the eastern tropical Pacific is preliminary and emphasizes that many aspects of the circulation are unknown. Present studies are underway to refine the
description of the boundary layer and the internal wave generation mechanisms. Further experiments will rely on long-term deployments to characterize the low frequency fluctuations.

Acknowledgements

I wish to thank D. Halpern for helpful discussions in the early stages of this research. This study was supported in part by the Deep Ocean Mining Environmental Studies (DOMES) Program of NOAA.

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