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Internal Waves on Continental and Island Shelves of the Open Ocean: A Comparative Analysis for Observations on the New York and Hawaii Shelves

V. G. Bondur, Yu. V. Grebenyuk, and K. D. Sabinin

Aerocosmos Scientific Center for Aerospace Monitoring, Gorokhovskii per. 4, Moscow, 105064 Russia
e-mail: vgbondur@aerocosmos.info, grebenyk@gmail.com, ksabinin@yandex.ru

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Abstract—Based on the results of processing experimental data obtained from measurements of current velocities and water temperatures on the United States Atlantic Shelf and near the Hawaii Islands (the island of Oahu and Mamala Bay), we perform a comparative analysis of the characteristics of internal waves in these representative areas of continental and island shelves of the ocean. These investigations indicate that the internal-wave fields in these areas are very different from one another in both the low- and high-frequency ranges. On the Atlantic Shelf, we have regularly observed tandems of powerful internal solitons clearly seen on space imagery of the oceanic surface. On the island shelves, soliton-type internal waves were less seldom seen as very specific oscillations. The absence of surface manifestations of even powerful solitons in Mamala Bay is explained both by the large pycnocline depth and by the fact that the vertical structure of these solitons is controlled by the second rather than the first mode, as it is on the Atlantic Shelf.

Key words: internal waves, baroclinic currents, internal wave, soliton, solibore, isotherm, thermocline, coherence, phase velocity.

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1. INTRODUCTION

Tandems of soliton-type internal waves (SIWs) are frequently found in oceans and seas, especially near continental shelves [1–4] and some underwater elevations of the open ocean such as the Mascarane Ridge and the Seychelles Islands [3, 4]. In all these areas, SIWs are clearly manifested on the oceanic surface as characteristic banding structures of alternating rips and slicks that are easily registered on space optical and radar imagery [1–4]. At the same time, these tandems were not found by their surface manifestations near such large inhomogeneities of the bottom topography as the Hawaii Ridge and other island elevations of the central Pacific [5–7]. Until now, it has not been clear whether this is caused by the absence of SIWs in these areas or whether they simply do not appear on the oceanic surface due to the large thermocline depth. Because the SIWs play a key role in the mixing of oceanic waters [8], it is of great interest to establish whether they can be found near bottom elevations of the open ocean within anticyclonic circulations.

Based on observational data for the United States Atlantic Shelf near Long Island and for the Hawaii islands (the island of Oahu), we tried to answer this question by comparing the background conditions with the characteristics of internal waves (IWs) in these two representative areas. Here, using the data of detailed measurements of current and temperature oscillations, we compared low-frequency IWs (internal tides and inertial waves) as major sources of SIWs with high-frequency IWs while particularly emphasizing tandems of intense waves.

2. COMPARISON OF BACKGROUND CONDITIONS IN STUDY AREAS

The bottom profile of the Atlantic Shelf at Long Island is shown in Fig. 1a. Figure 1c shows a typical distribution of the buoyancy frequency in this area. Here, two IW systems are generated. The first propagates from the generation area at the shelf edge northwestward (i.e., toward the coast), while the second wave system is generated south of the Hudson Canyon area and moves along isobaths.

The water basin at the island of Oahu is located in the area of Hawaii Ridge, which is also characterized by the intense generation of tides. The main feature of this ridge is that its slopes are of supercritical steepness, which leads to the generation of local internal tides at depths of 500–1000 m rather than over the

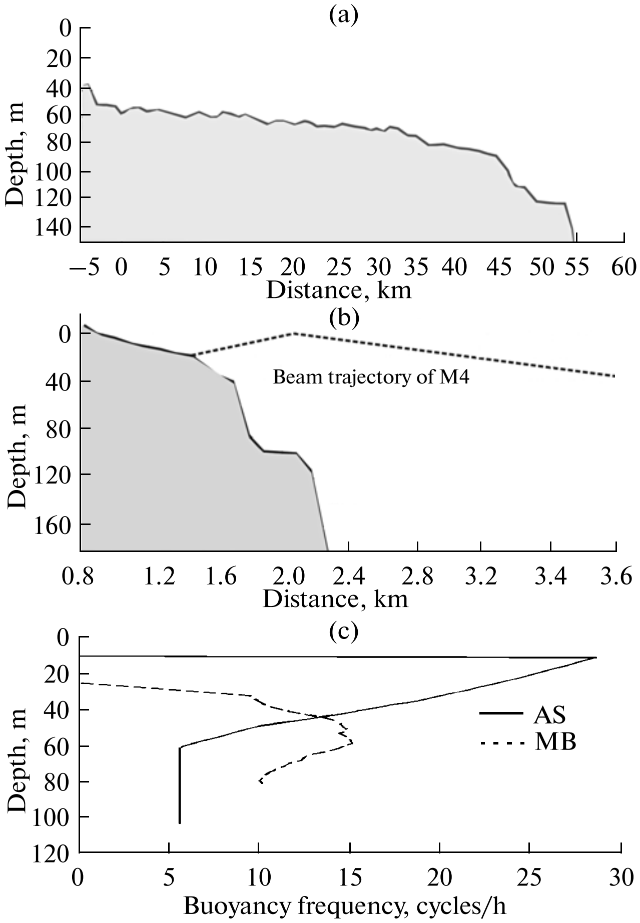

Fig. 1. Bottom profiles (a) of the Atlantic Shelf, (b) in Mamala Bay, and (c) the typical profiles of buoyancy frequency in these areas.

shelf edge, as happens normally [1, 5, 6, 9–17]. Figure 1b shows the bottom profile of Mamala Bay at the island of Oahu; it can be seen from here that the very thin and steep shelf of the bay from the shore becomes a very steep slope as far as 2 km away. The strongest semidiurnal internal tides in Mamala Bay are caused by remote sources over dams in the bay on both sides of Oahu.

Figure 1c shows a typical distribution of the buoyancy frequency in Mamala Bay in summer.

3. DATA USED TO CALCULATE THE PARAMETERS OF INTERNAL WAVES

The characteristics of IWs on the Hawaii shelf were calculated using the results of minutely measurement profiles of currents and temperature conducted in 2004 with the help of two bottom ADPs (Bv, Cv) and four anchored garlands (AT-DT) which were installed on the shelf edge of the island of Oahu (Mamala Bay) [9, 13, 18]. The temperature was measured at 8 levels in the thermocline (at a depth between 23 and 72 m) and the currents were measured at 2 m each in the 4–76-m layer. Density stratification data obtained with the help of a Microstructure Measurement System (MSS) were also used [9, 13].

The characteristics of IWs on the Atlantic Shelf were calculated using the results of current-profile measurements conducted with the help of a bottom ADCP on the shelf edge at a depth of 103 m in the 1995 SWARM experiment [3]. The measurement period was from July 20–30, 1995, with a 1.5-min step at 22 levels located at depths from 11 to 95 m (4 m each).

The original experimental data were processed with a preliminary and a special technique. The preliminary processing included smoothing current arrays according to depth with the help of a low-frequency third-order Butterworth filter with a cutoff frequency of 100 cycles/km; time filtering by band, low-frequency, or high-frequency sixth-order Butterworth filters; and the generation of data arrays of isotherm-depth oscillations.

Highly irregular vertical profiles of currents in Mamala Bay become reasonable only for values smoothed at no less than 10 m (Fc = 100 cycles/km). The measurement data of currents on the Atlantic Shelf obtained with the help of a 4-ray ADCP are more accurate and, therefore, generally used without smoothing.

The special processing included a calculation of the following parameters: current components related to the surface and internal waves, empirical orthogonal functions (EOFs), spectral characteristics of current oscillations (including spectral invariants and distributions by frequency and wave numbers), isotherm distributions and the relationship of their oscillations with oscillations of currents, and phase velocities of waves.

4. COMPARATIVE CHARACTERISTICS OF LOW-FREQUENCY WAVES

Existing publications point to the relatively simple character and predominantly local generation of internal tides (ITs) on the Atlantic Shelf [2–4, 7], as well as to the complex and highly variable structure of the IT field on the Hawaii shelf [6, 7, 10, 13], where orbital currents often reveal an unusual cyclonic character of circulation (counterclockwise).

Here we present some new findings obtained on the basis of minutely data after a corresponding smoothing with respect to depth and time. Figure 2 shows plots of the ratio of spectra of right- and left-hand circulations of internal-wave currents in Mamala Bay and on the Atlantic Shelf. An analysis of Figure 2 indicates that, in the lower layer of Mamala Bay, left-hand (cyclonic) circulation at tidal frequencies is dominant,

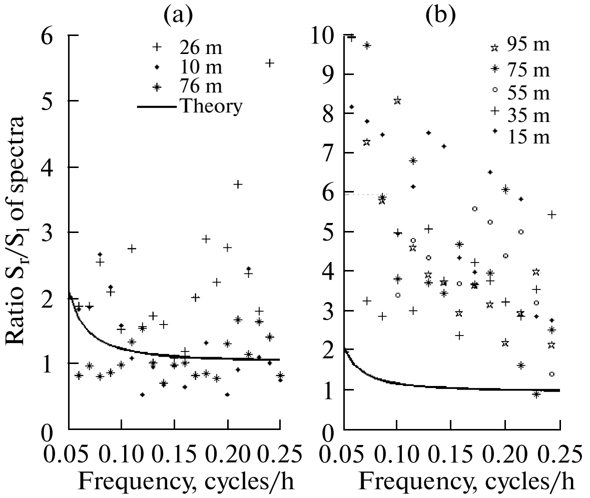

Fig. 2. Ratio S_r/S_l of spectra of the right-hand and left-hand rotation of internal-wave currents (a) in Mamala Bay and (b) on the Atlantic Shelf at distinct depts.

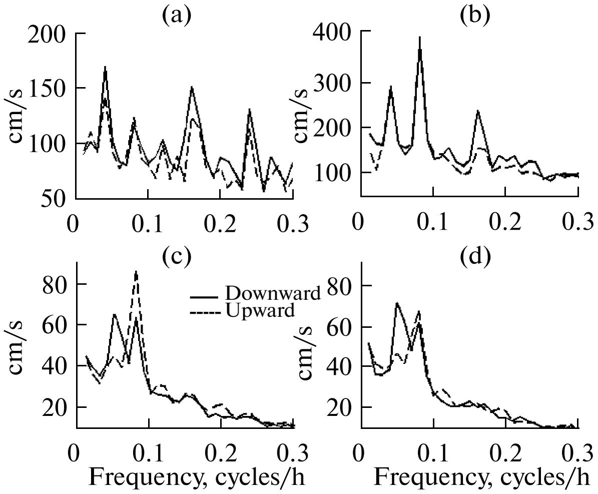

Fig. 3. Comparison between the spectra of upward and downward currents of (a, c) transverse and (b, d) longitudinal internal waves (a, b) in Mamala Bay and (c, d) on the Atlantic Shelf.

while the circulation is regular (anticyclonic) everywhere on the Atlantic Shelf, although the orbits became thickened due to the instability of directions. However, for the Atlantic Shelf too, the ratio of rotational components is significantly higher than the theoretical value (bold line in Fig. 2), which should be in Sverdrup waves.

Let us note that, hereafter in this section, the internal-wave motions were separated out of the general field by subtracting the zero mode of EOF, which just characterizes the field of currents of the surface tide in the domain under study. The simple subtraction of vertically averaged currents (as is customary) yields a baroclinic component of the field, which also involves the currents of the surface tide near sharp inhomogeneities of the bottom topography [11].

Now, let us compare the frequency spectra of internal-wave currents in the areas under study by differentiating between the waves with upward energy (upward IWs) and downward energy (downward IWs). This can be done by summing the spectral density in corresponding quadrants of two-dimensional spectra by frequency and vertical wave number using the Wentzel–Kramers–Brillouin (WKB) method (a transformation of the axis of depths) [19]. Figure 3 compares one-dimensional spectra in Mamala Bay and on the Atlantic Shelf.

The calculations of these spectra for the waves differing in vertical direction indicated that the longitudinal currents in Mamala Bay belong mainly to the IW of the lowest-mode M2. The transversal currents in Mamala Bay are related to the M4 IW with a clear dominance of downward waves and with a significant role played by 4-h waves. The spectra also involve diurnal waves with a symmetric vertical spectrum of longitudinal currents but with a dominance of downward waves in the field of transversal currents. In general, the spectra of transversal currents are more complex than those of longitudinal ones. In the spectra of transversal currents, the 6-h and 4-h harmonics are stronger than the semidiurnal M2, have higher modes, and are relatively symmetric but with the prevalence of the motion of downward energy.

It can be seen from Fig. 3 that the spectra of the Atlantic Shelf are much simpler and weaker than those of Mamala Bay. At tidal frequencies of the Atlantic Shelf, only semidiurnal M2 waves are found. Here, unlike inertial oscillations, the spectrum of transversal M2 waves is almost vertically symmetric. This speaks to a certain remoteness of the wave source that is sufficient for the generation of vertically coincident modes. As was supposed in [3], the IWs are generated south of the observation site. On the contrary, the spectrum of transversal M2 waves is asymmetric, with a dominance of upward motion characteristic to beam propagation from the source located close to the observation site. At the inertial frequency, downward waves are dominant.

In the transversal waves of Mamala Bay, the downward diurnal 6-h (M4) and 4-h (M6) waves are dominant; here, semidiurnal (M2) waves are weakly expressed and no inertial (0.03 cycles/h) waves are found. The asymmetry of spectra indicates that the corresponding waves are locally generated. The well-expressed diurnal and semidiurnal transversal oscillations have symmetric spectra; this is very consistent with their nonlocal generation [11]. However, the

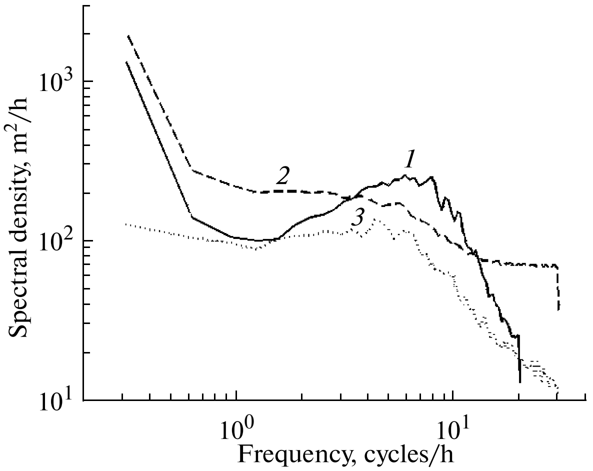

Fig. 4. Spectra of vertical velocities measured (*1*) on the Atlantic Shelf and (*2*) in Mamala Bay; (*3*) the spectrum of vertical velocities in the bay estimated on the basis of oscillations of the central isotherm of pycnocline.

downward components induced near the observation site are dominant in 6-h waves.

In the diurnal tide of Mamala Bay, the waves incoming from remote sources over the dams on the island of Oahu are dominant [14–17]; therefore, one can fully expect the transversal oscillations to be dominant and the spectrum in the vertical (the lowest mode) to be symmetric. The asymmetry and significant dominance of M4 transverse oscillations in the spectrum with a weakly expressed M2 point to a local generation of 6-h waves. This is quite explicable, because the generation of 6-h IWs in this area becomes possible due to the fact that, for M4 waves, the shelf slope in the bay coincides with the beam slope, whereas no such critical slope at the shelf edge can be found for M2 waves (see Fig. 1b).

The calculations of the level of coherence between the oscillations of the central isotherm of pycnocline and the projection of baroclinic currents on different directions confirm this finding. For velocity oscillations across isobaths, the maximum of coherence for the M4 IW is equal to 0.80 at a phase difference of 75°. For transverse oscillations on the M2 IW, the coherence is slightly lower (0.67) at a phase difference of 66°. In addition, the isotherm shifts and horizontal velocities are evidently related; here, the velocity outruns the shifts by 75°, which additionally confirms that the M4 wave is generated locally. In the oblique wave with downward energy going from the shore (just like with upward energy going to the coast), the phase difference should be 90°, which is close to the measured value.

A calculation of the two-dimensional wave spectrum yields (common for the whole layer) the dominance of the motion of 6-h downward waves; i.e., the M4 wave goes from the coastal portion of the shelf predominantly downward and into the open ocean. This wave is radiated around 1.3–1.5 km away from the coast, where the shelf slope is close to the critical value for the IW M4 (Fig. 1b). A portion of the energy is also radiated upward, and the corresponding characteristic (bean core) touches the oceanic surface around 2 km away from the coast.

5. COMPARATIVE CHARACTERISTICS OF HIGH-FREQUENCY INTERNAL WAVES

As was indicated in the Introduction, the study areas differ mainly in the presence of solitons on the Atlantic Shelf, which are almost inappreciable in Mamala Bay. Below we consider both the spectral characteristics of low-period internal waves (LPIWs) and individual tandems.

5.1. Spectral Characteristics of LPIWs

A detailed description of the spectral characteristics of LPIWs in Mamala Bay can be found in [12]; here, we present some basic results of this paper. Figure 4 shows the vertical velocity spectra calculated on the basis of measurement data on the Atlantic Shelf and in Mamala Bay.

In the velocity spectrum on the Atlantic Shelf, one observes peaks caused by soliton tandems, which are poorly manifested in Mamala Bay. The powerful high-frequency peak in the spectrum of the Atlantic Shelf is less expressed in Mamala Bay even in regards to isotherm oscillations. The stability and narrowness of IW-ellipses on the Atlantic Shelf is essentially higher. However, the waves (soliton tandems) on the Atlantic Shelf propagate not only along the normal to isobaths, which is testified to by “rotund” ellipses and by an angle of 20°–30° between the directions of ellipses and isobaths. This indicates that there is a second source located southeast of the observation site. The most stabile and narrow ellipses on the Atlantic Shelf are observed in the range between 4 and 10 cycles/h, whereas the corresponding range is 2–4 cycles/h in Mamala Bay, where the ellipses are directed across the isobaths but their larger thickness and lower stability speak to the higher instability of directions.

Let us compare the phase velocities of dominant waves on the Atlantic Shelf and Mamala Bay using the method proposed in [20, 21], which is based on continuity equations for the two-dimensional case. The method is as follows. For example, if a wave with an arbitrary smooth profile propagates along the *Oy*-axis with a phase velocity C_y, its orbital velocity at some level will be $V(t, y) = V(p)$, where $p = (y - C_y \times t)$ and t is

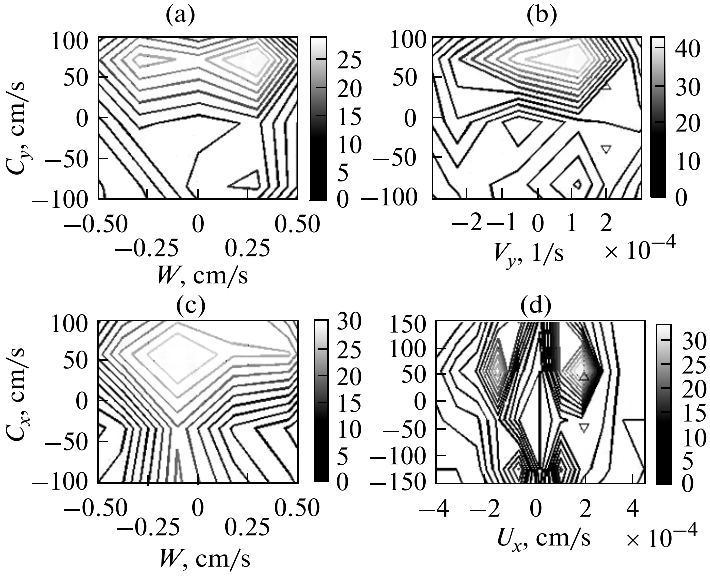

Fig. 5. Histograms of (a, c) phase velocities C_y, C_x and W and (b, d) horizontal divergences V_y and U_x for (a, b) 15-min transverse waves and (c, d) 10-min longitudinal waves on the Atlantic Shelf.

time. Differentiating V with respect to the rule of complex function, we obtain

$$dV/dt = -dV/dp \times C_y, \quad dV/dy = dV/dp.$$

It follows from here that $dV/dy = -(dV/dt)/C_y$, which, in view of the continuity equation $dV/dy = -dW/dz$ yields $C_y = (dV/dt)/(dW/dz)$, where W and z are the vertical velocity and direction, respectively.

This method can be easily extended to the case of a sinusoidal wave.

The depth-averaged spectrum of baroclinic currents calculated on the basis of measurement data on the Atlantic Shelf shows a peak at a frequency of 4 cycles/h for component V directed across isobaths and peaks of around 6 cycles/h for components U and W directed along isobaths. Linking the spectral peak of V (4 cycles/h) with transverse waves and the peak of U (6 cycles/h) with longitudinal waves, we estimated the phase velocity C_y in a narrow range of frequencies around 4 cycles/h and velocity C_x around 6 cycles/h. The velocities were estimated at recording points with strong signals and slight noises, i.e., for large gradients dWz of vertical velocity but weak shears of background currents and for large Vt and low Ut (Vt and Ut are derivatives of velocities) in estimating C_y, and the reverse in estimating C_x.

In the 47–65-m layer, we performed 269 estimates for the phase velocity C_y and 360 estimates for C_x. The general pattern of phase velocities and corresponding parameters of orbital currents W and horizontal divergence of bottom currents is shown in three-dimensional plots in Fig. 5.

It can be seen from the histograms shown in Fig. 5 that the dominant waves are those with velocities of around 0.7 m/s, which correspond to soliton velocities. In Mamala Bay, the number of LPIWs was smaller, which is related to the weak formation of solitons [12].

5.2. Tandems of LPIWs

Tandems of LPIWs on the Atlantic Shelf. It is well known (see, for example, [2, 3, 7]) that the Atlantic Shelf is characterized by systematically appearing tandems of intense internal solitons like those shown in Fig. 6.

To estimate the phase velocities of individual waves, we chose levels and times when the signals Vt and dWz were strong and the shear pollution by background currents was negligible.

Tandems of LPIWs in Mamala Bay. The results of comparisons between the oscillations of currents and isotherms indicated that analyzing individual tandems in Mamala Bay required smoothing ADP data more strongly. Only after a 20-m-depth smoothing of currents and low-frequency (smaller than 6 cycles/h) filtering did we manage to obtain some similarity of vertical motions of isotherms to oscillations of layers estimated with the help of integrated vertical currents. However, one cannot expect full similarity because the estimation of thermocline oscillations by vertical velocity (Eulerian description) differs from the Lagrangian tracking of isotherms.

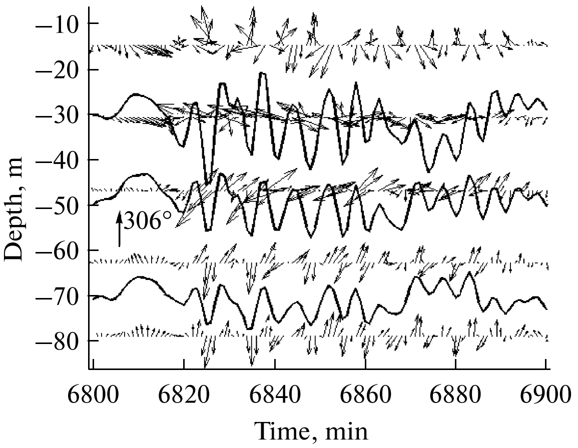

Fig. 6. Horizontal baroclinic currents (arrows) and layer shifts (lines) estimated with the help of integrated vertical velocities (in the range from 0.5 to 10 cycles/h) in a tandem of solitons passed over the shelf edge (point *D* of the SWARM-95 experiment, with a depth of 103 m and coastal direction of 306°). Time step is 1.5 min.

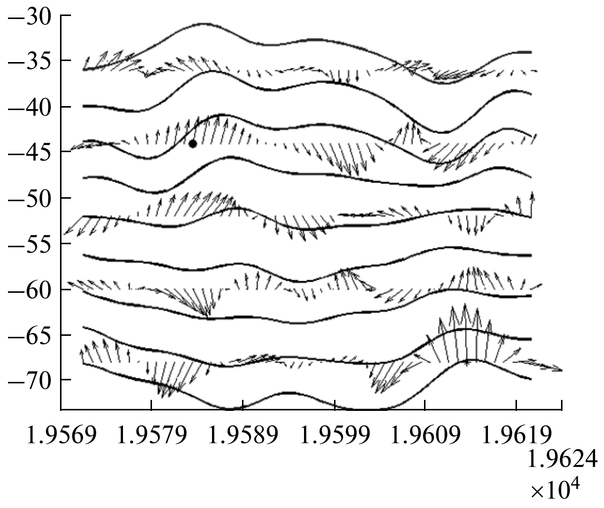

Fig. 7. Estimate of the phase velocity of a wave propagating across isobaths on the basis of measurements in Mamala Bay (station Bv) at the 19585th minute of observations in the layer between 47 and 55 m. The arrows denote the directions of horizontal baroclinic currents, and the lines stand for layer shifts estimated with the help of integrated vertical velocities (in the range from 0.5 to 10 cycles/h) in the tandem of solitons.

To estimate the phase velocity of the wave propagating across isobaths at the station *Bv*, we chose a point in the current registration corresponding to the 19585th minute of observations in the layer between 47 and 58 m, where all quantities to be estimated had sufficiently high values (Fig. 7). In this layer, the current phase velocities that can distort data due to "shear pollution" [22] were small. The calculations indicated that the wave moves into the ocean with a velocity of 37 cm/s, which is lower than the expected velocity of solitons, and the change in oscillations with depth testifies to the fact that there are higher modes.

In another tandem at the 213th hour of observations, the pattern of oscillations of isotherm 27°C is similar to bottom solitons, but the estimate of oscillations of layers and currents in the layer of 0.5–6 cycles/h according to ADP data indicates that waves are multimode. Although the velocity estimates for waves propagating across isobaths in the tandem differ, both estimates yield a direction to the coast. This tandem is characterized by large waves with a period of 20–40 min and not of the lowest mode, propagating to the coast with a phase velocity of $C = 0.2–0.5$ m/s. Despite the pattern of isotherm oscillations, which is similar to bottom solitons (elevation solitons), the character of the field of currents and layer oscillations estimated by ADP data contradicts the solitons interpretation for the nature of this tandem.

The abovementioned estimates for layer oscillations by vertical velocity and by isotherms in LPIW tandems are very consistent and indicate that for the most part the waves of the lowest mode are dominant, but no clear markers of solitons can be found. This is testified also by the fact that the pattern of oscillations is uncertain and the phase velocities of waves propagating across isobaths are small. It should also be noted that, due to the strong 20-m-depth smoothing of currents and large distances between thermistors (5–10 m), higher mode manifestations are dampened. The oscillations of thermocline in LPIW tandems are clearly expressed in oscillations of isotherms and in the field of currents (see Figs. 8a–8e).

6. CONCLUSIONS

Using a comparative analysis of measurements of current oscillations and temperatures on the shelf edge in Mamala Bay and on the United States Atlantic Shelf at Long Island, we have studied the main features and differences in the IW fields in these representative areas.

Unlike on the continental Atlantic Shelf, where the semidiurnal IWs generated at the shelf edge are dominant in the tidal frequency range, on the island shelf in Mamala Bay, waves of nonlocal origin are dominant and quaddiurnal (along with semidiurnal) IWs are well expressed. The local generation of semidiurnal IWs in Mamala Bay is reduced due to the steepness of the shelf, but they can occur episodically when the favorable stratification of density and currents appears. At the same time, quaddiurnal IWs can be generated regularly because the slope of their beams is close to the

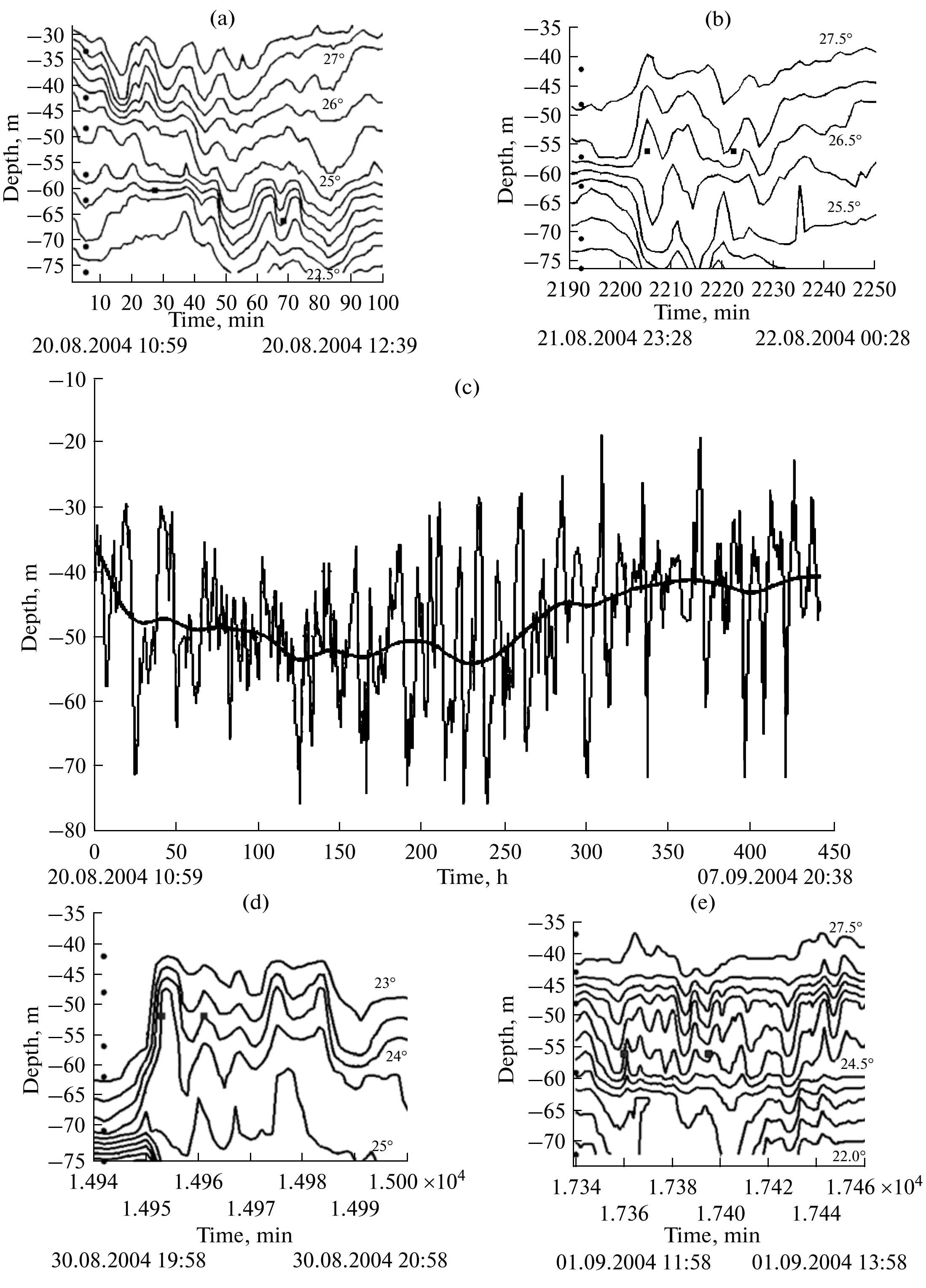

Fig. 8. (a, b, d, e) Oscillations of isotherms in well-smoothed tandems of LPIWs on the background of low-frequency oscillation of (c) thermocline in Mamala Bay: (a) Aug. 20, 2004, 10:59–12:39; (b) from Aug. 21, 2004, 23:28 to Aug. 22, 2004, 00:28; (d) Aug. 30, 2004, 19:58–20:58; (e) Sept. 01, 2004, 11:58–13:58; (c) bold lines indicate oscillations smoothed by filtering with <0.5 cycles/h.

shelf slope in the bay. The local generation of quaddiurnal IWs is confirmed by the asymmetry of vertical spectra of currents. In Mamala Bay, one can also find diurnal IWs, but almost no inertial oscillations are found. On the Atlantic Shelf, on the other hand, inertial waves not only are well expressed, but also critically influence the generation of internal solitons [7].

Powerful internal solitons regularly (often twice a day) emerge as tandems and/or solibores of the lowest mode on the United States Atlantic Shelf at Long Island [2, 3]; in Mamala Bay, soliton-type IWs appear more rarely and as very specific oscillations that are similar to solibores but have a vertical structure differing from the Atlantic Shelf. In solibores of the Atlantic Shelf, the sharp jump in the pycnocline is accompanied by a tandem of quasi-sinusoidal linear waves, while the forefront is like stairs of opposite signs in the upper and lower parts of the pycnocline (the second mode) in solibores of Mamala Bay and the oscillating "tail" is expressed less clearly with an indication that both the second and first modes exist.

The amplitude of pycnocline jumps exceeds 10 m, and their propagation rate is close to the phase velocity of low-frequency IWs of the second mode, just as it should be in solitons. The weak difference of velocities of high-frequency waves in the tail indicates that either their structure is low-mode or these waves are solitons as well.

Generally speaking, on the basis of measurements at a single vertical, it is difficult to distinguish a solibore from a generating tandem of solitons because, in the latter, the sharp front of a leading soliton is also followed by quasi-periodic oscillations, which, in fact, are vertices of solitons located close to one another and disbanding further due to amplitude dispersion [19].

The records of tandems in Mamala Bay show that part of the oscillations following the sharp front also is related to solitons of the second mode. Weaker oscillations in the tail of tandems are linear waves of the lowest mode that keep up with solitons due to the fact that their velocity is close to the propagation rate of second-mode solitons.

The polarity of stairs in these specific tandems, which can be conditionally called solibores of the second mode, depends on the depth of pycnocline, the upper part of which has dips when its position is high and spikes when its position is low (Fig. 8). The dominance of the actuation of the second mode in Mamala Bay, rather than of the first mode as on the Atlantic Shelf, is explained by the insufficiency of the velocity of currents generating soliton tandems.

Thus, the IW fields in the study areas are strongly different in both low- and high-frequency ranges. Although Mamala Bay is also characterized by solitons that have considerably emerged, their nature, as well as their frequency of emergence (sporadic and relatively rare), is strictly different from the characteristics of solitons on the Atlantic Shelf. The absence of surface manifestations of even powerful internal solitons on the island shelf in Mamala Bay is explained not only by the large depth of the pycnocline, but also by the fact that the vertical structure of the most noticeable solitons is controlled by the second mode (rather than by the first mode, as on the Atlantic Shelf). The episodic appearance of strong internal solitons in Mamala Bay is caused by rare strong cross-slope currents of ITs that are essential to the generation of internal solitons. In the ITs of Mamala Bay, along-slope orbital motions are dominant [12].

It can be supposed that the characteristic features of the IW field revealed in Mamala Bay are inherent in other sets of islands of the open ocean as well.

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