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Observations of Internal Waves of Tidal Period made with Neutrally Buoyant Floats[1]

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ABSTRACT

Neutrally buoyant current floats at depths between 500 and 2500 m at 28° 12′N, 139° 07′W and 28° 48′N, 117° 41′W exhibited a marked periodic motion. The floats moved in clockwise orbits at speeds of 5–18 cm/sec and with a period of approximately 25 hours. The orbital is approximately equal to the inertial period. Floats tracked simultaneously at different depths were not in phase. With one exception, such motion has not been observed at other latitudes. It is believed that the observed motion was a result of internal waves and that such motions are restricted to a rather narrow belt of latitude.

Introduction. Observations of the deep currents now being made with Swallow's neutrally buoyant floats (Swallow, 1955, 1957; Swallow and Hamon, 1960; Knauss, 1960a) contradict the earlier concept of slow net transport of ocean water at great depths, for it has been found that the deeper water moves at much higher speeds than was previously suspected. The motion is not predominately tidal; with one notable exception (Swallow, 1955), it is difficult to see any tidal component at all in the measurements so far reported.

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TABLE I. Pertinent data concerning the ten floats tracked at three stations for more than 35 hours on Limbo. Depth estimates of the floats are no better than plus or minus 200 m. The translational velocity is the mean velocity over the entire time the float was tracked. Except for Float B (tracked in reference to a buoy that was dragging its anchor) and Float N (not tracked long enough to remove its orbital movement), all speeds are good to at least 0.2 cm/sec.

Float	Depth (m)	Launched Time (GCT)	Tracking Time (hours)	Translational Velocity (cm/sec)
Station 1, 28° 12′N, 139° 07′W				
B	1200	2150/23 May	122	2.4–235°
C	1350	1710/25 May	215	0.6–267°
E	700	0625/ 1 June	48	3.6–192°
G	900	0010/ 5 June	79	1.8–220°
H	2150	0100/ 6 June	223	1.7–253°
I	1050	0954/ 9 June	153	1.9–264°
Station 2, 23° 00′N, 133° 46′W				
J	2300	1933/17 June	59	1.4–337°
L	1650	2134/18 June	52	2.1–094°
Station 3, 28° 48′N, 117° 41′W				
M	1450	0030/26 June	68	2.6–204°
N	3900	0630/26 June	35	$\leq$ 2.6–317°

This paper describes some observations in the eastern North Pacific where the motion of neutrally buoyant floats was mostly periodic, with a period of about 25 hours. Floats tracked simultaneously at different depths were not in phase. The floats moved at speeds of 5–18 cm/sec. It is believed that internal waves produce the motion and that these waves are restricted to a rather narrow belt of latitude.

Results. Swallow's neutrally buoyant floats are sealed aluminium tubes which, because they are both lighter and less compressible than sea water, can be so weighted that they will float at any desired depth. By equipping the floats with sound transducers they can be tracked as they move with the currents. The construction of the floats and the method of tracking were similar to those first described by Swallow (1955). The floats were tracked relative to a taut wire buoy anchored to the bottom (Knauss, 1960b).

During a 45-day cruise (Limbo, May 16-July 1, 1960) of the Scripps Institution of Oceanography's R. V. Horizon, a total of ten floats at three stations was tracked successfully for periods in excess of 36 hours (Table I). With one exception[3], all floats at Sts. 1 and 3 exhibited a marked periodic

3 The one exception was our first float, Float B. On Limbo, we initially tried to use an "improved" anchoring system for our taut wire buoys which did not work. As a result, Float B was tracked relative to a moving reference point. Although this added complication makes the interpretation of the movement of Float B difficult, it appears likely that if Float B did move clockwise it had a small orbit.

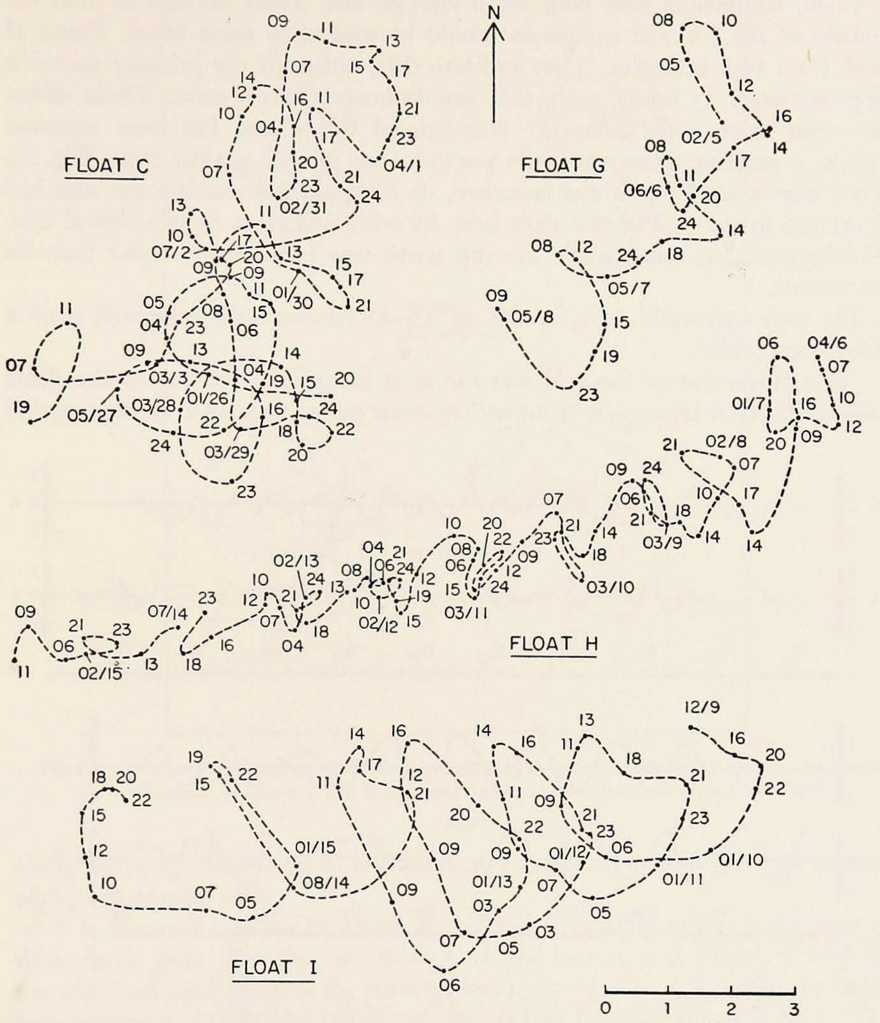

Figure 1. Motion of four floats at St. 1. Each dot represents a three-bearing "fix" whose circle of error is generally less than 200 m. The time to make such a fix is approximately an hour. The time (GCT) and date of each fix is indicated. Other pertinent data are noted in Table I.

motion. These two stations were at nearly the same latitude (28° 12′N and 28° 48′N respectively), but St. 3 was some 2200 km to the east of St. 1. Neither of the two floats at St. 2, some 600 km to the south, gave any clear indication of this orbital motion.

Examples of float movement are shown in Fig. 1. In each case the orbital speed is several times that of the translational velocity. In a few cases the nonperiodic component was both small enough and steady enough so that the nature of the periodic component could be studied in some detail. Floats H and I are two examples. They indicate that, although the primary period is approximately 25 hours, more than one frequency was present. These effects are seen more easily after the translational component has been removed (using a running mean) and the positions are plotted against time (Fig. 2). Four days after Float I was launched, its orbit along a north-south axis had increased by 60%, but two days later its orbit was close to its original size. Furthermore, its speed while moving north was considerably faster than on its return.

On two successive days, speeds of 16–18 cm/sec were observed over a four-hour period.

The movement of Float H was the most complicated of any of the floats observed. What began as a "routine" 25-hour period became a 12-hour period

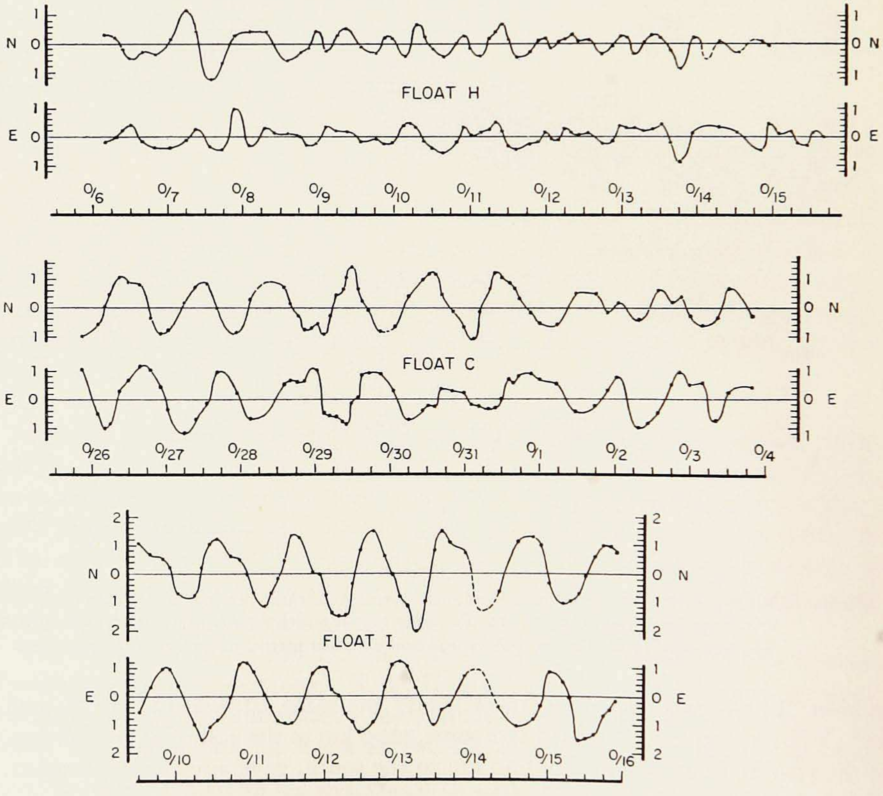

Figure 2. North-south and east-west components of movement plotted against time after removing the translational motion. The units of the ordinate axis are kilometers. Time (GCT) is plotted along the abscissa.

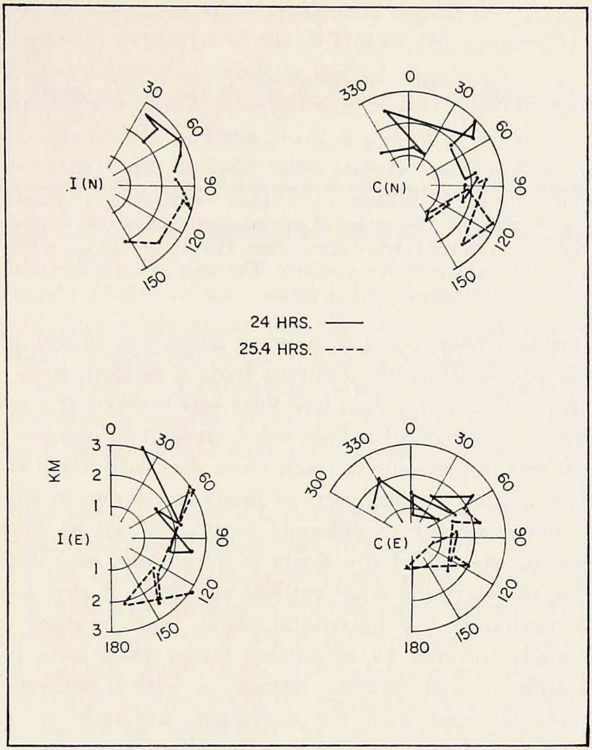

Figure 3. Measure of the phase shift of the maxima of the north-south and east-west components of motion of Floats C and I, assuming first a 24-hour and then a 25.4-hour period.

along the north-south axis. It is difficult to resolve any regular periodic motion along the second axis.

It is of some interest to know as exactly as possible what the periods of these floats were. For the two floats with the best records (Floats C and I), the amplitude and phase of the maxima were plotted; first a period of 24 hours was assumed and then a period of 25.4 hours (the inertial period[4] at 28° 12′N). If the records were sine curves at those frequencies, the points would fall together, all at 90°. If the true period were less than the assumed period, each succeeding maximum would plot at a smaller phase angle (the points would rotate counter-clockwise). Conversely, if the true period is greater than that assumed, the points will rotate clockwise. As can be seen in Fig. 3, the true period seems to lie somewhere between 24 and 25.4 hours.

If it could be assumed (which it probably cannot) that the four records are mutually independent, then the difference in these periods is significant. How-

[4] The inertial period is the period of a Foucault pendulum. $T_p = 12$ hours/sine φ, where φ is latitude.

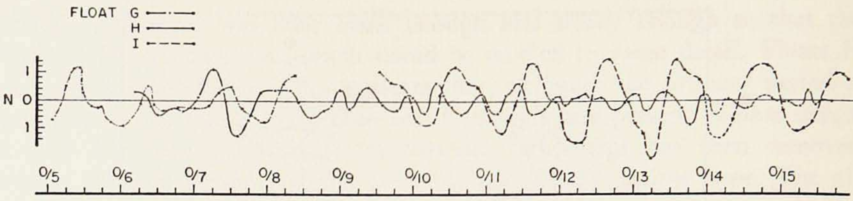

Figure 4. The north-south component of motion (after removal of the translational movement) of Floats G, H, and I plotted against time. The depths of the three floats were approximately 900, 2150, and 1050 m respectively. The units of the ordinate axis are kilometers.

ever, the variation from point to point is large, and in any given record, the movement is not significantly different from a random walk.

Insofar as possible, more than one float was tracked at a time, but in order to get successive positions of a float often enough to observe the details of its movement, it was not feasible to track more than two floats at once. Examples of the relative motion of such pairs of floats are shown in Fig. 4. They show clearly that floats moving at different depths are not in phase.

The observed motion of the floats is horizontal, and with these floats it is not possible to determine what vertical velocities, if any, are associated with this orbital motion in the horizontal plane. Such vertical motion (internal waves) is usually inferred by measuring temperature as a function of time, either by a series of hydrographic stations or with a bathythermograph. It is not practicable (at least with the techniques available on Limbo) to track floats and make hydrographic stations simultaneously; as a result, no long series of hydrographic stations is available. A 48-hour series of BT's indicates that the vertical movement of the isotherms is no greater at this location than one might expect anywhere in the open ocean (Fig. 5). The BT extends only

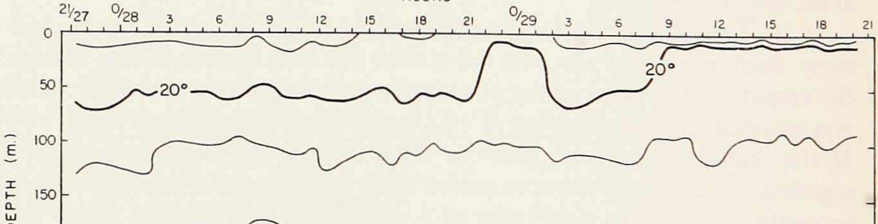

Figure 5. A 48-hour BT series made by taking a BT each time the ship stopped for a bearing. Times of the BT observations are noted by ticks along the bottom of the figures. All BT's were taken within a 7 km radius of the anchored buoy at St. 1.

to 250 m and all of the floats were tracked at depths of 500 m and greater; therefore, the negative evidence of the BT does not necessarily preclude the possibility of greater vertical motion at deeper depths.

With one possible exception, no evidence of this type of motion has been observed at other locations. Swallow tracked a float at 2700 m in the Pacific for 42 hours on the Scripps 1957 Mukluk expedition; this float showed strong evidence of having a clockwise rotational motion of about 6 cm/sec and a period of 14 hours. The inertial period at the location of the float (52°32′N, 141°45′W) is 15.1 hours.

Since the motion of floats in deep water is in general erratic (*i.e.*, turbulent), one might question to what extent periodic motion might be hidden in the high noise level of the observed turbulence. The turbulent component observed on floats in the Pacific is usually very small, and an orbital speed of even 5 cm/sec would be easily distinguishable above the background. It therefore seems unlikely that such motion could have gone unobserved in previous work.

Discussion. The motion observed is not simply an expression of tidal movement. In the first place, the predominant tide along the west coast of North America and on the islands in the eastern and central North Pacific is semidiurnal while the motion of the floats is predominately diurnal. More important, however, is the observation that floats at different depths are not in phase and that the speeds are 2–5 times those expected for open ocean tides.

Although the observed movement is assumed to be completely in the horizontal plane, it should be noted that the methods of measurement preclude the observation of vertical motion. However, it can be shown that free internal waves of inertial period have no vertical motion, but have only rotary horizontal motion similar to that described (Fjeldstad, 1933).

The explanation for these internal waves can probably be accounted for by the latitude of the observations. Defant (1950), Haurwitz (1950) and Proudman (1953) have all drawn attention to the possible generation of internal tides of inertial period. Proudman (1950: sect. 168) has discussed the problem of a forced internal wave (in an infinite, two-layer ocean of constant Coriolis force) where the period of the forcing function is long enough so that the Coriolis force is an important parameter. Both the period of the forcing function (T) and the inertial period (T_p) appear in the solution; and to a sufficient approximation, resonance is achieved when $T_p^2 = T^2$.

The idea of considering the latitude bands of the earth as tuned circuits, each tuned to its own inertial period, is an appealing one in considering an explanation of the observations discussed in this paper. In the vicinity of 29° latitude the ocean is tuned to the diurnal components of the tide-producing forces. Presumably at about 75° latitude one would find similar motion, with a period of approximately 12.4 hours and related to the semidiurnal tidal components. At latitudes which are out of tune with the periods of these tide-producing forces, no such waves are to be expected. However, this hypothesis does not account for the appearance of a certain amount of semidiurnal motion as observed with Float H.

It should be noted, moreover, that the solution is for a two-layer ocean, that is, one in which there is no rotary motion in the horizontal plane. Furthermore, the coupling action between the tide-producing forces and the internal waves is not discussed. A complete explanation of the results reported here will have to await a fuller theoretical treatment than is presently available.

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