The Role of Internal Tides in the Nutrient Enrichment of Monterey Bay, California[a]

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Semidiurnal internal tides in Monterey Canyon are shown to be partially responsible for macronutrient enrichment of surface waters in Monterey Bay, California. CTD time series at five stations in the canyon revealed the presence of semidiurnal internal tides with heights between 50 and 120 m.

Thermistor data demonstrated an internal tidal bore at the head of the canyon. Data and theory suggest that internal tidal bores may be breaking, due to either shear instability or direct overturning, thereby enriching the immediate area near the canyon head.

Transects normal to Monterey Canyon showed a 20-m thick lens of 12 °C water moving out of the canyon at high internal tide. This lens was then pinched off from the canyon, and led to a density-induced divergence. The nutrient transport associated with the internal tidal divergence could support as much as 30% of the daily primary productivity in the northern part of Monterey Bay during non-upwelling periods.

Introduction

In this note, we discuss the role of macronutrient enrichment by internal tides in Monterey Canyon, California (Figure 1). Wind-induced upwelling south of Monterey Bay probably has a greater overall effect on the productivity of the area during the spring and summer (Broenkow & Smethie, 1978), but during non-upwelling periods, enrichment due to internal tides may play a significant role in the primary production of the bay.

The idea of internal tidal mixing as an enriching mechanism is not new. Cooper (1947) postulated that internal waves in the English Channel, impinging at right angles to the continental slope, would run up the slope. As this cold, nutrient-rich water moves closer to the surface, vertical mixing due to wind waves and surface cooling (during the winter) would enrich the surface layer. Cooper also suggested that submarine valleys or canyons might concentrate the energy of the internal waves into contracting cross-sections and project deeper water into the surface layers.

The objectives of this study were (1) further to characterize semidiurnal internal tides in Monterey Canyon, since the first published evidence of internal tides in Monterey Bay were from one 25-h time series (Broenkow & McKain, 1972); (2) to demonstrate that these

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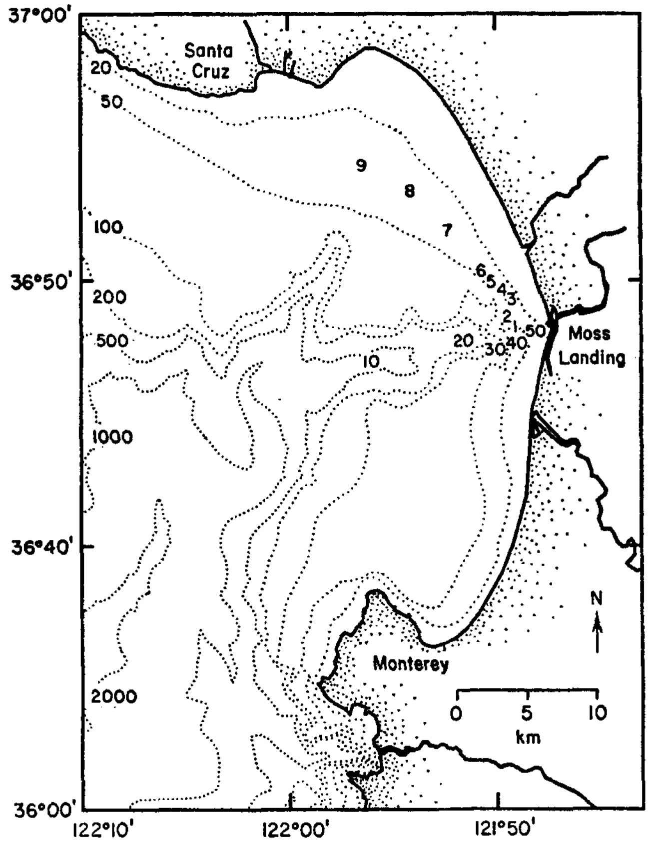

Figure 1. Monterey Bay station locations, August 1971 through November 1979. Depth contours are in meters.

internal tides are capable of transporting cold, nutrient-rich waters to the surface; and (3) to estimate the amount of enrichment due to internal tides in terms of the daily photosynthetic fixation rate.

Data discussed here are taken from a variety of studies in Monterey Bay. Broenkow & McKain (1972) obtained a 25-h hydrocast time series of temperature, salinity and nutrients at Stations 30 and 50 on 7 and 8 August 1971 (Figures 1, 2). CTD profiles were obtained at Station 10 approximately every 2 h for 20 h on 6 and 7 May 1976. The same method was used again at Stations 20 and 40 on 13 and 14 November 1978. Then, stations were occupied about every 1·5 h over a 13-h period. From 5 through 13 October 1979, a continuous record of bottom temperature was made from a thermistor placed at 25 m at the head of Monterey Canyon (Figure 2).

CTD profiles were also used to trace the movement of water out and over the canyon flanks. A CTD section north of, and normal to, the canyon axis along the 20-fathom contour was made at both high and low predicted internal tides on 13 and 14 September 1979 (Figure 1). High and low internal tides were predicted from the previous day's CTD time series in the canyon.

On 8 and 9 November 1979, the vertical distribution of dissolved reactive phosphate was examined on the same 20-fathom transect north of the canyon's axis at times of both high and low predicted internal tide, based on a short CTD time series the previous day (Figure 1).

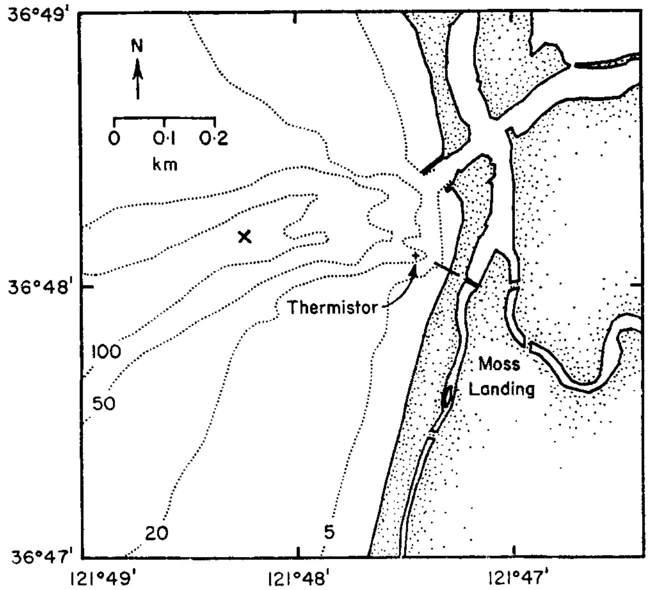

Figure 2. Details of bathymetry (contours in meters) near head of Monterey Canyon and thermistor location 5–13 October 1979. × shows position of Station 50, August 1971.

The first objective of this study was to demonstrate the general occurrence of semidiurnal internal tides in Monterey Canyon. Existing, relatively short hydrocast and CTD time series (Figures 3, 4, 5) all suggest that internal waves of diurnal periodicity are common in the canyon. Spectrum analysis of a 7-day thermistor record (Figure 6) at the Monterey Canyon head demonstrates more conclusively that these waves had predominantly semidiurnal periodicity. Cross-spectrum analysis of the thermistor data and predicted surface tidal heights indicated a phase lag of 7 h at the dominant 12-h period.

The greatest internal tidal heights observed in Monterey Canyon ranged from 50 to 120 m (Figures 3, 4, 5). Heights in the lower part of the range are comparable to the 50-m heights of the semidiurnal internal tide found in the continental slope break off Norway (Keunecke, 1971, 1972). Similar results have been found by Reid (1956) and Carsola (1967) off the California coast. The greatest height observed in Monterey Canyon (120 m) is comparable to observations reported by Magaard & Krauss (1967) near the Iceland–Faeroe Ridge, where they observed semidiurnal waves as high as 100 m. Although the heights reported in this study were greater than those reported for internal tides found in most other locations (Halpern, 1971; Schott, 1971; Roberts, 1975), even larger waves have been observed. For instance, Bockel (1962) has observed waves of up to 180 m in the Straits of Gibraltar.

The large semidiurnal internal tides reported in this paper probably result from the topography of Monterey Canyon. Roberts (1975) concluded that, near coasts, the height of the semidiurnal internal tide is influenced by bottom topography. Keunecke (1971, 1972) found that heights are generally less than 10 m outside the shelf region, about 50 m at the shelf break, and about 20 m on the shelf. Small amplitude wave theory predicts that long waves moving into shallow water should show an increase in height, while the period remains constant. This appears to be the case for semidiurnal internal tides observed in Monterey Canyon, where the narrowing and shoaling of the canyon cause a focusing of wave energy.

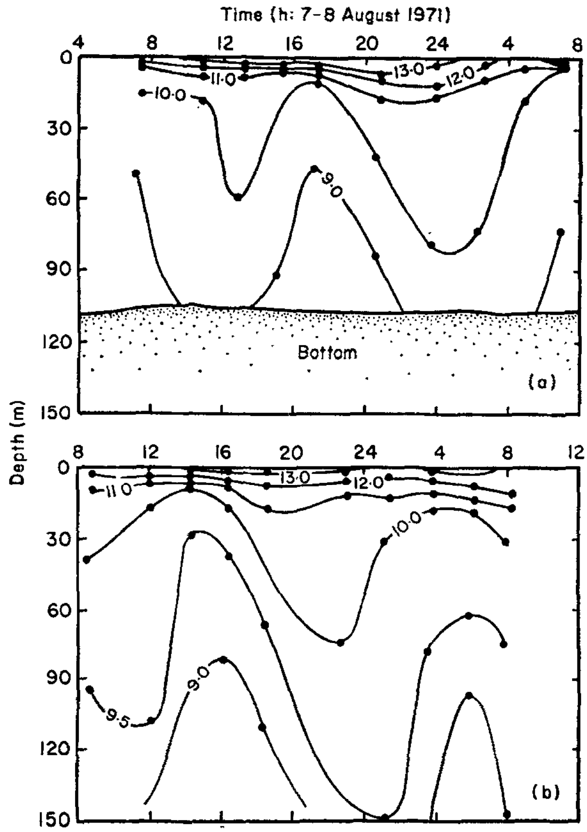

Figure 3. Distributions of temperature (°C) at (a) Station 50, 1 km west of Monterey Canyon head and (b) Station 30, 4 km west of Monterey Canyon head, 7 and 8 August 1971.

When the amplitude of an internal wave is no longer small with respect to water depths, as occurs at the Monterey Canyon head, the wave profile changes during its shoreward travel (Defant, 1961). Cairns's (1967) data from Mission Beach, California, showed that the internal wave became asymmetric as it entered shallow waters. The asymmetry became more pronounced with increasing wave height, and higher amplitude waves assumed the characteristics of internal tidal bores. An internal tidal bore is characterized by a rapid increase in temperature at a fixed position, in which the advancing water forms an abrupt front. Thermistor data from the Monterey Canyon head indicated the presence of such a bore (Figure 6) by the 3·8 °C h^{-1} temperature change.

Breaking internal waves may be an important mechanism for oceanic mixing. Cacchione (1970) investigated shoaling of both high- and low-frequency internal waves in a linearly stratified wave tank. He found generally that low-frequency waves over a steep slope and high-frequency waves over a shallow slope both develop considerable turbulence. The latter characterizes the situation observed in this study. Hall & Pao (1971) showed that shoaling internal waves break by a shearing motion when ripples on the wave crest become large. This mechanism would be pronounced for highly steepened waves, such as those we have observed at the head of Monterey Canyon.

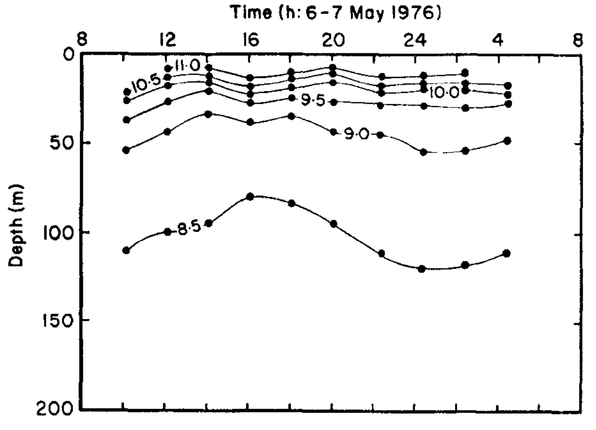

Figure 4. Distribution of temperature (°C) at Station 10, 13 km west of Monterey Canyon head, 6 and 7 May 1976.

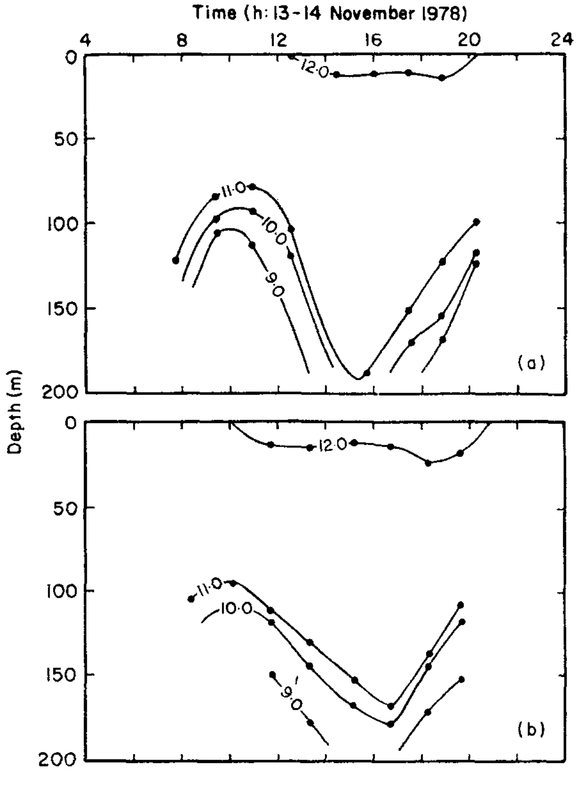

Figure 5. Distributions of temperature (°C) at (a) Station 40, 3 km west of Monterey Canyon head, and (b) Station 20 6·1 km west of Monterey Canyon head, 13 and 14 November 1978.

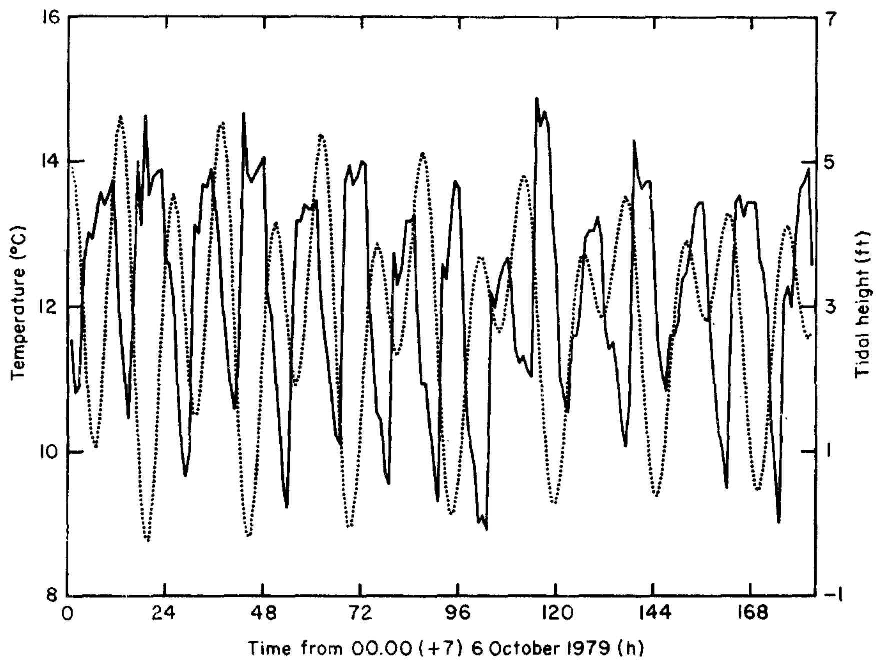

Figure 6. Bottom temperature (—) and predicted surface tidal height (. . . .) at Monterey Canyon head 6–13 October 1979. Digitizing interval was 60 min.

Some indirect evidence exists to support the mixing effects of internal waves at Monterey Canyon head. A station at the head of the canyon near the location of the thermistor used in the October 1979 study (Figure 2) showed consistently lower values of oxygen saturation than at another station 0·5 km seaward (Broenkow, 1980). The yearly mean oxygen saturation difference was about 15%. However, from May through August, the difference was about 36%.

Observations of temperature distribution seaward of the canyon head and over the canyon flanks suggest that a second internal tidal enriching mechanism is at work. As the main thermocline, or isotherms below the main thermocline, rises above the canyon rim,

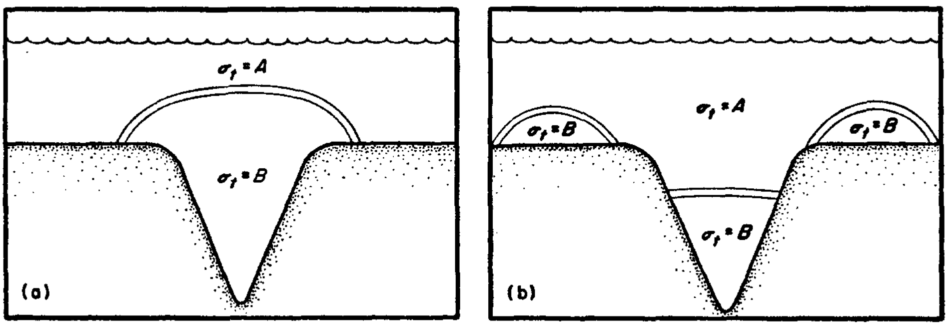

Figure 7. Conceptual model of internal tidally induced flow for (a) high and (b) low internal tides.

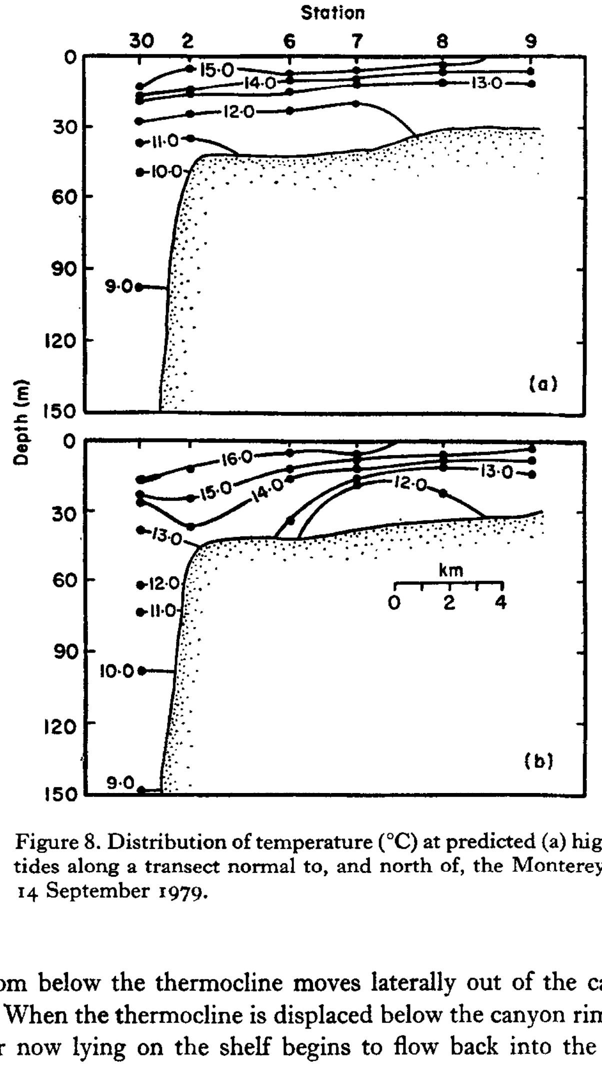

Figure 8. Distribution of temperature (°C) at predicted (a) high, and (b) low internal tides along a transect normal to, and north of, the Monterey Canyon axis. 13 and 14 September 1979.

denser water from below the thermocline moves laterally out of the canyon and over the shelf (Figure 7). When the thermocline is displaced below the canyon rim on the falling tide, this dense water now lying on the shelf begins to flow back into the canyon (Figure 7). However, some of this water at the outer edge is left behind due to mixing, surface heating and inertia.

Volume convergence (on the falling tide) and divergence (on the rising tide) and associated shelf-break current speeds were calculated considering volume continuity of 11 °C water at Stations 20 and 40 during a tidal cycle on 13 and 14 November 1978 (Figure 5). The volume change of this water type was estimated using simple trapezoidal canyon geometry and the observed rise and fall rate of specific isotherms. Details of the method are given in Broenkow & McKain (1972). It was estimated that a volume of 520×10^6 m^3 (6 h)$^{-1}$ was pumped alternately into and out of the canyon, requiring horizontal velocities over the canyon rim of between 2 and 4 cm s^{-1}. Associated up- and down-canyon velocities would be on the order of 4 to 8 cm s^{-1}. Computed up- and down-canyon velocities are of similar magnitude as current-meter observations in Monterey Canyon (Dooley, 1968; Njus, 1968; Caster, 1969; Gatje & Pizinger, 1965). Data from Broenkow & McKain (1972) yield a volume convergence of 240×10^6 m^3 (8 h)$^{-1}$, which is consistent with average lateral velocities of about 13 cm s^{-1} across the edge of the canyon. These calculations are sensitive to canyon bathymetry which

TABLE 1. Distribution of PO_4^{3-} (μmol l^{-1}) along a transect normal to and north of the Monterey Canyon axis at high and low predicted internal tide, 8 and 9 November 1979. Mean PO_4^{3-} concentration calculated between 5 and 30 m

	Station					
z (m)	30	1	3	6	7	9
Low internal tide						
5	0·39	0·35	0·79	0·81	0·82	0·71
20	0·60	0·77	1·00	0·40	0·95	0·58
30	0·89	1·02	0·86	0·73	1·20	1·36
50	0·69					
100	1·43					
150	1·53					
Mean PO_4^{3-}	0·59	0·69	0·91	0·59	0·96	0·78
High internal tide						
5	0·50	0·62	0·41	0·71	0·62	0·25
20	1·07	0·85	1·09	1·06	1·01	0·76
30	1·25	1·24	1·27	1·24	0·66	1·17
50	1·20					
100	1·57					
150	1·88					
Mean PO_4^{3-}	0·93	0·86	0·92	0·99	0·82	0·69

could account for the differences between these estimates, since station positions and internal tidal characteristics were different for the two studies.

The area of Monterey Bay affected by internal tidally induced density flow was calculated from volume continuity. It is estimated that for a 20-m thick lens of water moving out of the canyon, an area of approximately 26 km^2 near the head of Monterey Canyon should be affected. Temperature profiles on 13 and 14 September 1979 support this estimate. During this study period, a 20-m thick lens of 12 °C water was observed moving northward out of the canyon at time of high internal tide [Figure 8(a)]. As the internal tide fell below the canyon rim, this lens of 12 °C water was pinched off from canyon water and remained over the flank of the canyon [Figure 8(b)]. Our estimate from continuity requirements place the edge of the affected area north of the canyon around Station 6 (Figure 1). Transect data showed that 12 °C water moved to Station 7 during time of high internal tide, but was not found at Stations 2 or 6 at time of low internal tide, when the 12 °C isotherm had fallen below the canyon rim [Figure 8(b)]. Thus, the oscillatory internal tide produced a net divergence above the canyon rim.

We have estimated the nutrient enrichment in Monterey Bay attributed to internal, tidally induced density flow. Phosphate data obtained on 8 and 9 November 1979 along the same CTD transect made previously showed an increase in PO_4^{3-} concentration from time of low internal tide to high internal tide at Stations 30 through 6 at 20 and 30 m (Table 1). The mean phosphate concentration between 5 and 30 m increased in a similar manner (Table 1). It may be noted that the largest increase in the mean PO_4^{3-} concentration occurred at Station 6 (where a 68% increase was observed). This represented a 0·4-μmol l^{-1} increase of phosphate in approximately 6 h. Stations 7 and 9 showed lower near-bottom concentrations at time of high internal tide, opposite from what the model predicts. This again suggests that Station 6 is the edge of the immediate effect of deep canyon water moving out over the flanks [note 12 °C water in Figure 8(b)]. As this water type is pinched off [Figure 8(b)], it would usually move northward away from the canyon, as flow in Monterey Bay is predominantly northerly throughout the year (Broenkow & Smethie, 1978). This northward-moving lens, isolated from canyon water, would account for higher phosphate concentrations at Stations 7 and 9 on the falling internal tide.

Potential primary productivity of northern Monterey Bay (about 400 km^2) could be significantly enhanced by this internal tide transport mechanism. The observed increase of 0·4 $\mu mol\ l^{-1}\ PO_4^{3-}$ from low to high internal tide could sustain an increased productivity of 0·6 $g\ C\ m^{-2}\ day^{-1}$, if there were a net volume divergence of 100% ($520 \times 10^6\ m^3\ (6\ h)^{-1}$. CTD temperature transects [Figure 8(b)] indicate that the net volume divergence could have been as great as 50%; that is, half of the total volume displaced over the canyon rim during one tidal cycle remained outside the canyon. If a net divergence of 50% is representative, then 0·3 $g\ C\ m^{-1}\ day^{-1}$ would account for approximately 30% of the daily primary productivity in the northern part of Monterey Bay during non-upwelling periods (Malone, 1971). This is a large portion of the production to attribute to internal, tidally induced density flow. During more productive upwelling periods, this mechanism would probably contribute proportionately less, of the order of 5 to 15%.

Finally, though local bathymetry and hydrography will vary the effects of this mechanism, it is suggested that internal, tidally induced flow is probably active in most submarine canyons around the world and will produce significant local nutrient enrichment and attendant biological effects.

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