HORIZONTAL TRANSPORT OF PHOSPHORUS IN THE CALIFORNIA CURRENT

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ABSTRACT

Horizontal transport of phosphorus (inorganic dissolved PO_4 and zooplankton P) to a depth of 200 m through an area of about 4.2 x 10^5 km^2 off California and Baja California has been calculated for four winter and six summer months of different years. Large seasonal and interannual variations occur in transport across CalCOFI lines 70, 80, and 110, and in the net P budget for the area. These variations are due to long-term changes in strength of the California Current and to small-scale, short-term variability caused by mesoscale turbulence and eddies. There is no correlation between upwelling indices and net P transport across lines by month. Mean summer and winter P transports were also calculated using CalCOFI PO_4 and geostrophic flow data from 1950 to 1978. The long-term mean transports for the area show a net export of about 300 g-at P/sec during winter and a net import of about 400 g-at P/sec during summer. This seasonal difference is probably due to (1) greater southward advection in summer and (2) higher mean phosphate concentrations throughout the area at all depths (0-200 m) during summer. Zooplankton contributes a mean of about 4 percent of the total P transports and budgets.

RESUMEN

Se calculó el transporte horizontal de fósforo (PO_4 inorgánico disuelto y zooplancton P) hasta una profundidad de 200 m por un área de aproximadamente 4.2 x 10^5 km^2, frente a California y Baja California, para cuatro meses de invierno y seis de verano de diferentes años. Ocurren grandes variaciones estacionales e interanuales en el transporte a través de las líneas 70, 80 y 110 de CalCOFI, así como en el presupuesto neto de P para este área. Estas variaciones se deben a cambios de largo período en la fuerza de la Corriente de California y también se deben a la variabilidad de pequeña escala y de corto período causada por turbulencia y remolinos de grande escala. No existe una correlación a través de las líneas entre índices de surgencia y el transporte P neto por mes. También se calculó el transporte P medio de verano y de invierno usando los datos CalCOFI de PO_4 y flujo geostrófico desde 1950 hasta 1978. El transporte medio de largo período para el área presenta una exportación neta de aproximadamente 300 g-at P/seg. durante invierno y una importación neta de aproximadamente 400 g-at P/seg. durante el verano. Esta diferencia estacional probablemente se debe a: (1) mayor advección hacia el sur en verano y (2) concentraciones fosfáticas medias más altas por todo el área y a todas profundidades (0-200 m) durante el verano. El zooplancton contribuye un medio de 4 por ciento del total de transportes P y presupuestos.

INTRODUCTION

The California Current off California, like most equatorward-flowing eastern boundary currents, has generally high primary productivity and high standing stocks of phytoplankton, zooplankton, and fish (Wooster and Reid 1963; Barber and Smith 1981). It is about 1000 km wide (Hickey 1979), with a gradient (increasing shoreward) of productivity and standing crop (Smith 1971; Owen 1974; Bernal and McGowan 1981) that begins about 500 km offshore and extends to, or near, the coast. Two important processes supporting this production are (1) advection of nutrient-rich water from the north, where nutrient concentrations throughout the water column are higher, and (2) coastal upwelling of nutrient-rich water.

Coastal upwelling drives a large part of seasonal variations in coastal production. Some of this production can be advected offshore a few hundred km in highly localized, ephemeral plumes (e.g., Traganza and Conrad 1981), but most effects probably do not extend much beyond 50 to 75 km offshore (Barber and Smith 1981). Long-term (interannual) variations in zooplankton biomass occur, however, from the coast out to about 500 km between Pt. Reyes and Cabo San Lazaro, an area of about 6.6 x 10^5 km^2 (Bernal 1979, 1981). These variations have little or no relationship to indices of upwelling (Bakun 1973; Chelton 1981); rather, they appear related to measures of advective strength of the California Current (Bernal and McGowan 1981; Chelton 1981). Bernal and McGowan argue that variations in zooplankton stocks off California and Baja California are due to fluctuations in abundances of species occurring only in those areas, hence the variations cannot be due solely to advection of northern stocks. They must result from variations in

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the area's underlying primary productivity. Productivity depends in part on available supplies of preformed nutrients, hence variations in advection of these nutrients from the north are probably responsible for part of the changes in zooplankton abundance. Here we attempt to quantify advection of the important plant nutrient phosphorus (P) into and out of a large region of the California Current (Figure 1).

METHODS

We used 1950-78 California Cooperative Oceanic Fisheries Investigations (CalCOFI) data (Table 1) on temperature, salinity, phosphate (PO_4), and zooplankton abundance. PO_4 was the nutrient most frequently sampled in both time and space.

The region analyzed (Figure 1: about 4.2 x 10^5 km^2) includes CalCOFI cardinal lines 70, 80, and 110, all out to station 90. Selection of these lines was based upon frequency of sampling and proximity to points for which Bakun (1973) calculated indices of upwelling derived from wind-stress (Figure 1). This latter criterion allowed us to compare variations in P transport across these lines with variations of upwelling indices. We investigated seasonal effects, considering cruises in December (month 12), January (01), and February (02) as "winter," and June (06), July (07), and August (08) as "summer."

Our transport calculations cover 0-200 m (*re.* 500 db) because of (1) data availability (PO_4 data from most CalCOFI cruises [Table 1] extend to at least 200 m); (2) the region's euphotic zone is always <<200 m (Owen 1974); and (3) 200 m is well into the thermocline and below the mixed layer during all seasons (Wyllie and Lynn 1971).

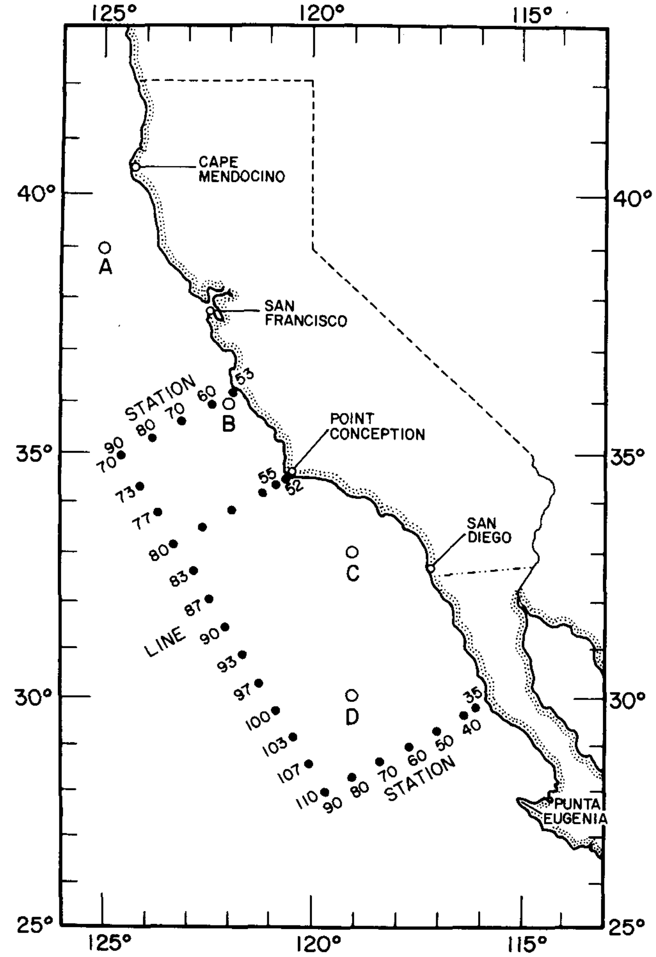

Figure 1. Region of the California Current for which phosphorus budgets were computed from transport across lines 70, 110, and the western edge (stations 90). Letters designate points for which Bakun (1973) calculated upwelling indices.

TABLE 1
CalCOFI Cruises Used for the Analysis of Horizontal Phosphorus Transport

5002*	(SIO**, 1960a)	6401[c]	(SIO, 1965a)	7008	(SIO, 1980b)
5007	(SIO, 1960a)	6407	(SIO, 1966)	7102	(SIO, 1980b)
5008	(SIO, 1960a)	6501	(SIO, 1965b)	7201	(SIO, 1980c)
5102[a]	(SIO, 1963a)	6507	(SIO, 1967)	7202	(SIO, 1980c)
5106[a]	(SIO, 1963a)	6806	(SIO, 1971)	7207	(SIO, unpublished data)
5107	(SIO, 1963a)	6901	(SIO, 1976)	7712	(SIO, unpublished data)
5108	(SIO, 1963a)	6902	(SIO, 1976)	7801	(SIO, unpublished data)
5112	(SIO, 1963a)	6906	(SIO, 1977)	7807	(SIO, unpublished data)
5508	(SIO, 1960b)	6907	(SIO, 1979)	7808	(SIO, unpublished data)
6107	(SIO, 1962)	6908[c]	(SIO, 1979)		
6301[b]	(SIO, 1963b)	6912	(SIO, 1980a)		

*First two digits = year, second two = month. Underlined cruises used to calculate individual cruise transport.
See Table 2 for limitations of these data sets.
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a Line 113
b PO_4 to 50 m only
c Some stations to less than 200 m, but not less than 100 m

PO_4 values were interpolated to standard depths 0, 10, 20, 30, 50, 75, 100, 150, 200, and 500 m. These data represent only dissolved inorganic P. We ignore dissolved organic P because little is known about its form and distribution (e.g., Corner and Davies 1971), and because it appears insignificant in phytoplankton ecology (Strickland and Solórzano 1966; Perry 1976).

Particulate organic P may occur as seston, bacteria, phytoplankton, zooplankton, and nekton; only zooplankton has been included here. There are no suitable data for bacteria and seston in the California Current. Phytoplankton has also been ignored because of lack of plant biomass data and because calculations using chlorophyll *a* measurements (Owen 1974) suggest that phytoplankton made up $<<1\%$ of inorganic P transport (both summer and winter, 1969). We did not treat P in fish and other nektonic organisms because the animals' mobility and migratory habits would probably invalidate any relation to water-transported dissolved inorganic P.

Zooplankton displacement volumes (ml/1000 m^3) were taken at the same stations as PO_4 data. P transported in zooplankton tissue was calculated as volume transport between adjacent stations (0-200 m) multiplied by the mean of those adjacent stations' zooplankton displacement volumes. Zooplankton transport was converted to P transport by assuming (1) displacement volume (cc) = wet weight (grams), (2) dry weight = 0.13 wet weight, (3) organic weight = 0.8 dry weight, (4) P = 0.02 organic weight, and (5) atomic weight of P = 31.

Geostrophic flows were referred to an assumed level of no motion at 500 db except in shallower water, where flows were referred to the deepest depth sampled. We did not make shallow-water corrections to geostrophic flow using the interpolation methods discussed in Reid and Mantyla (1976) because the available data do not include stations shallower than 500 m on either the northern or southern lines. North-south transport was calculated across CalCOFI station lines 70, 80, and 110 (Figure 1); east-west transport was calculated across a western boundary formed by station 90 on all lines between 70 and 110 (inclusive). Flow calculations used MLRG (SIO) program CADV, based on Sverdrup et al. (1942: p. 463).

Transport of PO_4 was calculated as geostrophic flow times mean PO_4 concentration. Mean PO_4 values were computed from concentrations at the four corners of each cell formed by two adjacent stations and two adjacent standard depths (e.g., station 70.80 at 75 and 100 m, and station 70.90 at 75 and 100 m). Each mean PO_4 value was multiplied by its corresponding volume transport to give PO_4 transport (g-at P/sec) for each cell. Cells were then summed vertically, east-west along lines, and north-south along the west edge to give net transport (0-200 m) of P across each line.

We made two estimates of P transport: (1) for seasons and years by using PO_4, volume transport, and zooplankton data from all cruises with complete data sets (underlined in Table 1) for winter and summer; (2) mean P transport over 29 years by using mean vertical distributions of PO_4 and volume transport from 1950 through 1978. In the 29-year mean analyses, all available PO_4 data for winter and summer (Table 1) were averaged for each depth at each station (Figure 2). Mean volume transports across lines 70, 80, and 110 were obtained from profiles of monthly mean geostrophic velocity from 1950 through 1978 (Figure 3, modified from Lynn et al., in press). For transport across the western edge, we used the overall mean summer and winter transports calculated in (1) above. For zooplankton, we used means obtained from individual cruises in (1) above.

Several aspects of the data limit both possible manipulations and confidence in calculated results. These are (1) problems of sampling design, (2) changes in analytical techniques between years, and (3) possible computational artifacts.

(1) Sampling and analyses for PO_4 were not always done to the same depth nor at a consistent set of depths. Many cruises sampled slightly (or radically) different station plans, and different years varied in areal coverage. Few cruises provided a complete data set for lines 70, 80, and 110 (Table 1); the cruises chosen represent the most complete available coverage (for any nutrient) by season and line. Similarly, few summer or winter cruises provide true replicate or duplicate sets of PO_4 observations. Consequently, spatial and temporal coverage are much less than ideal, and the data set is internally heterogeneous.

(2) Analytical and/or sampling techniques changed from 1950-78. From 1965 to 1969 (excepting a few cruises in 1966), hydrographic casts using Nansen bottles were supplemented by casts using salinity-temperature-depth (STD) recorders. At any given station, these casts were not simultaneous in time and space. When bottle casts did not go to 500 m, or when no bottle cast was made at an STD station, we have used STD data for geostrophic flow calculations. Each 1969 cruise included T and S data from both STD and bottle casts. In 1972, only STDs were used. Cruise 7712 and all 1978 cruises used bottle cast data for T and S. We have not assessed any errors or biases introduced by this variety of sampling techniques.

Before 1968, measurements of PO_4 were made manually with a spectrophotometer. From 1968 on, a Technicon AutoAnalyzer (AA) was used. Hager et al. (1972) showed the two methods to be comparable;

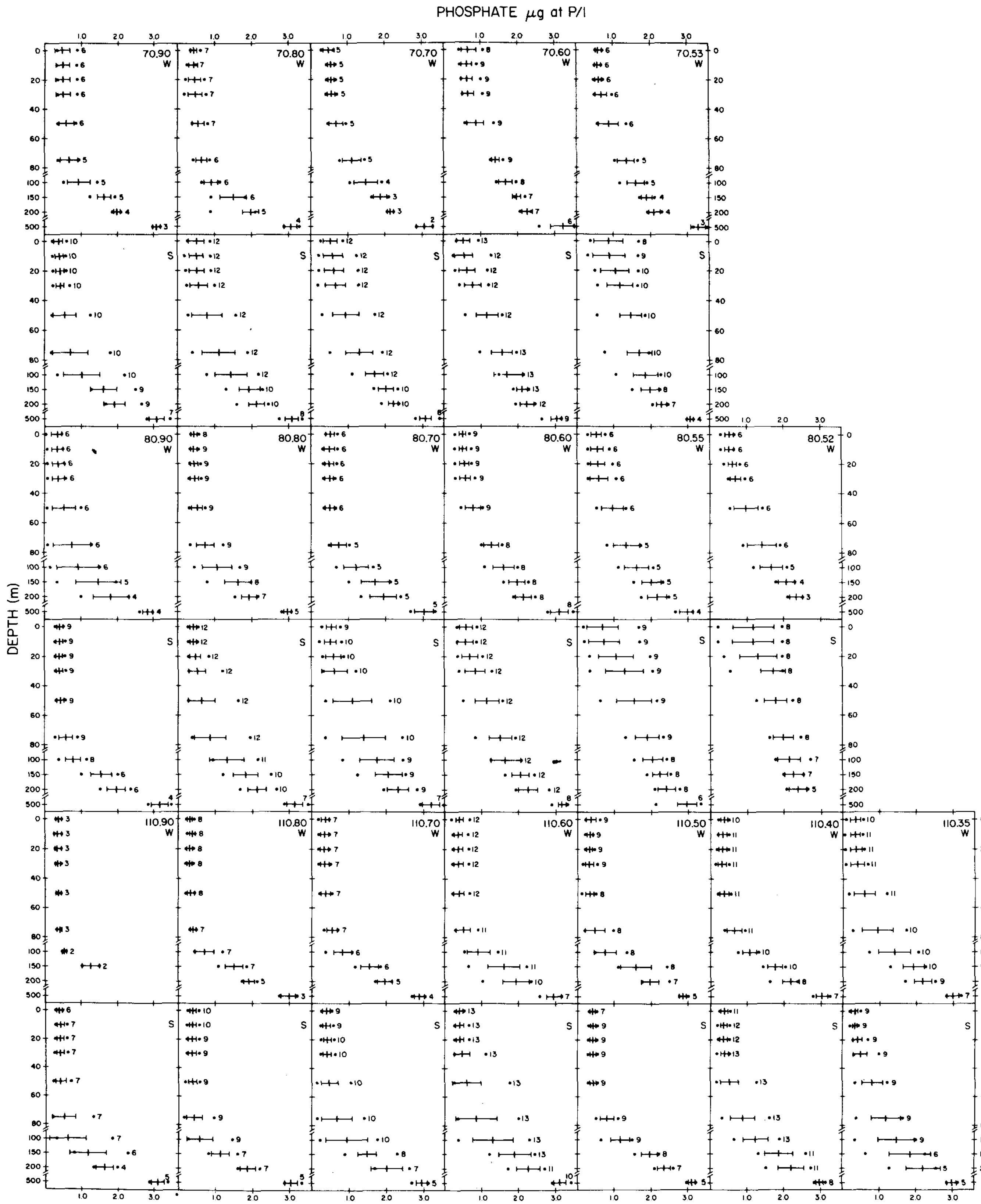

Figure 2. 1950-78 mean winter (W) and summer (S) vertical profiles of PO_4 from 0 to 500 m for CalCOFI lines 70, 80, and 110. Central heavy vertical bar = mean; horizontal bar = ± 1 S.D.; dots = range. Number of samples is beside each upper range dot.

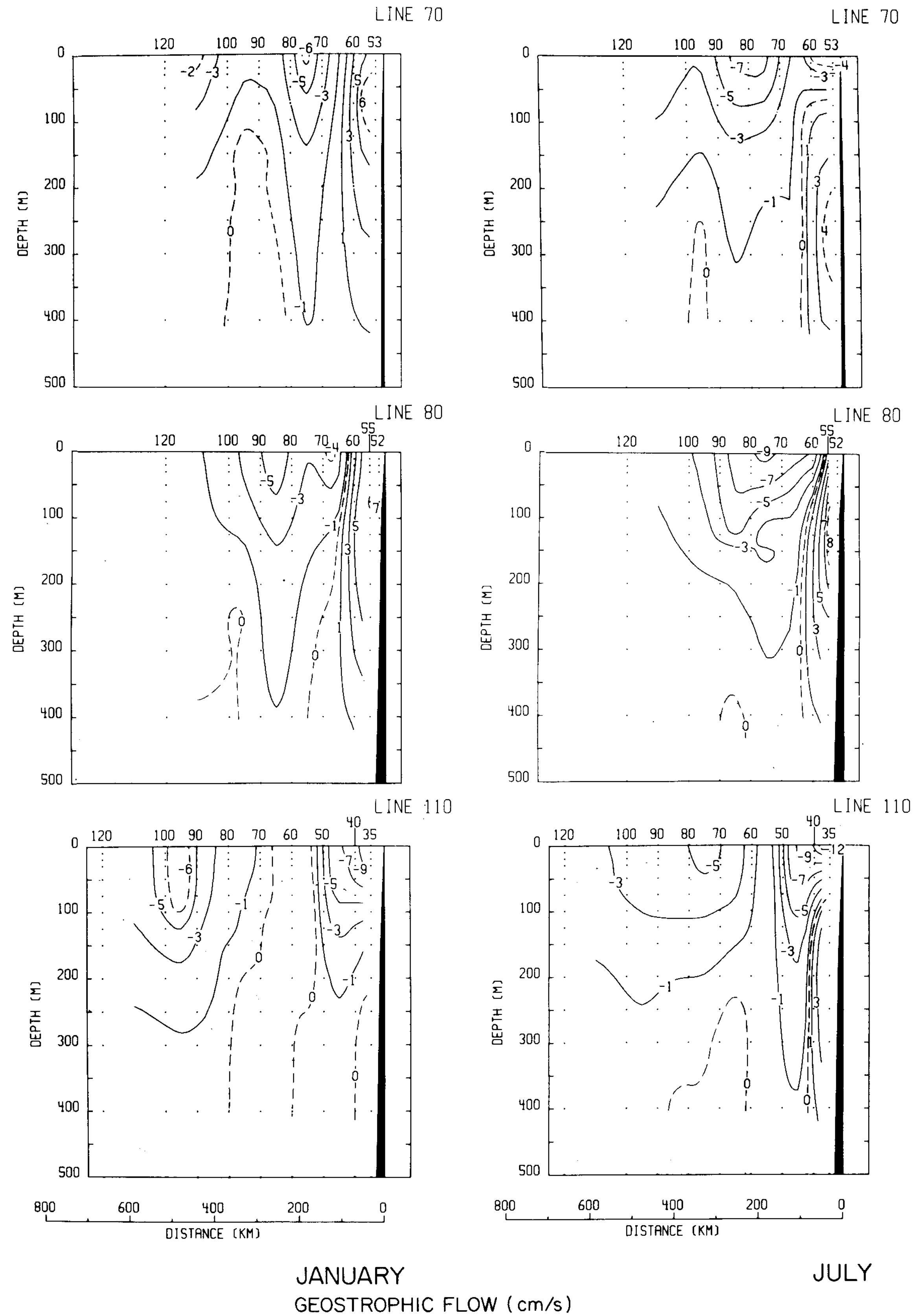

Figure 3. 1950-78 mean January and July geostrophic velocity profiles for CalCOFI lines 70, 80, and 110. Velocity in cm sec^{-1}; flows south are negative, north are positive (from Lynn et al., in press).

however, in routine AA work (as on CalCOFI cruises), baseline drift is a problem that renders absolute P values less reliable than in spectrophotometric data. We assumed no differences in accuracy and precision between methods, and combined all years' data in obtaining 1950-78 statistics.

Zooplankton sampling design changed over the years (Smith 1971, 1974; Smith and Richardson 1977). Sampled depths were 0-70 m (1950), 0-140 m (1951-68), and 0-210 m (1969 onwards). Displacement volumes for 1951-68 have been adjusted to be comparable to 0-210-m volumes (per Smith 1971). No conversion factor is available for 1950 volumes; this causes a slight increase in the zooplankton contribution to calculated P transport for 1950. Changes in mesh size and net type that occurred during the period were also ignored.

(3) Potential computational artifacts exist, especially in geostrophic flow calculations. If 500 db is not a true level of no motion (see "Discussion"), 0-200-m flow may be superimposed upon a deeper flow for which we cannot compensate accurately. In addition, any error in reference level will probably not apply uniformly to all four lines of stations.

Nearshore, shallow-water regions are potentially important contributors to mass-balance calculations. Chelton (1980) showed that high-frequency (>1 cycle yr^{-1}) variations in steric height do not match sea-level changes, which implies the existence of either deeper flows or significant currents between shore and the first offshore station. Further, shallow water is likely to have the greatest upwelling and most vigorous lateral transport. Unfortunately, these nearshore regions (with their attendant problems in geostrophic flow computations) have not received sampling sufficiently intensive to allow us to either incorporate their flows directly into our calculations, or to apply shallow-water corrections (Reid and Mantyla 1976).

Nutrient data also had to be manipulated. In a few cases where bottles were very widely spaced, interpolations for up to three depths between bottles have been made. In a few other cases the terminal value for a depth profile was extrapolated. On three cruises noncardinal lines were used (Figure 1; Table 1) because cardinal lines were not sampled. The footnotes of Table 3 list limitations of other data sets.

RESULTS

We calculated mass balances for water transport (0-200 m) using individual cruise geostrophic flows and mean 1950-78 January and July geostrophic velocities. Geostrophic flow estimates contain by far the largest potential sources of error (selection of level of no motion and inability to include nearshore transports) in PO_4 transport calculations, and are therefore discussed before other results dependent upon them.

TABLE 2
Mass Balance of Flow through Area*
Flow across boundaries

Cruise	Line 70	Line 110	West side	Net
		Winter		
5002	1.2880	−2.7460	1.9083	0.4503
6501	2.9091	−2.2340	0.3993	1.0744
6902	0.1107	−1.4003	1.4835	0.1939
7801	0.4794	0.7299	0.8861	0.6356
				$\bar{x}$ = 0.5886
				s.d. = 0.3711
		Summer		
6107	2.2979	−2.7885	1.5862	1.0956
6407	1.9003	−3.4782	2.0590	0.4811
6507	1.6534	−0.7582	0.2734	1.1686
6907	1.7743	−1.5955	0.2734	0.4522
7807	2.4616	−2.9153	0.6965	0.2428
				$\bar{x}$ = 0.6881
				s.d. = 0.4165
		1950-1978 Mean		
Winter	0.1793	−1.3585	0.9232	−0.2560
Summer	1.2771	−2.3467	1.3282	0.2586

*Units are Sverdrups (10^6 m^3 sec^{-1})
Flow in is positive, flow out is negative.

All net budgets for individual cruises (Table 2) are positive; mean input to the area is 0.64 Sv sec^{-1} (std. dev. =± 0.37). This suggests (1) a consistent difference between lines in how well the assumption of no motion at 500 db is met, (2) failure to account for the wind-driven surface Ekman transport, or (3) failure to include nearshore flows. The third possibility, as mentioned above, cannot be addressed with our data. Considering the assumption of no motion at 500 db: Wyllie (1966, Chart 4) gives a 1960-65 mean geostrophic flow at 500 m *re.* 1000 db. There is a steric height difference of about 2 dyn cm at 500 m between lines 70 and 110.Wyllie also shows northward flow at line 70, southward flow at line 110, and a weak net eastward flow across the western edge. Accordingly, our estimates of transport would be too large across line 70 and too small across both line 110 and the western edge. The result is an overestimate of the net flux into the area, agreeing with the positive bias shown in Table 2.

Considering surface Ekman transport: Parrish et al. (1981) presented figures of mean surface transport by quarter for the California Current region. For winter and summer, there is no net across-line transport at lines 70, 80, and 110. Transport out of the area across the western boundary was about 0.6 Sv sec^{-1} in winter and 0.9 Sv sec^{-1} in summer. The seasonal difference agrees with the difference in our mean seasonal inputs. The good agreement in magnitude is

TABLE 3
Summary of Horizontal Phosphorus Transport* during Individual Cruises

	Winter					Summer				
Line	70**	80**	110**	West†	Net†† budget	70**	80**	110**	West†	Net†† budget
					Inorganic dissolved phosphate					
1950	1184a	−311b	1577	916	523	1002	1311	ND	2555	—
1961	ND	ND	ND	ND	—	2461	1627	1959	1161	1663
1964	ND	ND	ND	ND	—	2035f	2300f	3261f	938	−288
1965	2781	988c	2194c	328	915	3076g	592g	97g	511	3490
1969	−291	946	766d	1357	300	1079	1062	951c	82	210
1978	325	−1217	93e	396	628	1878	815	1114	253	1017
Mean	1000	102	1158	749	591	1922	1285	1476	917	1363
					Zooplankton phosphorus					
1950	8	−32	49	166	125	47	20	—	42	—
1961	—	—	—	—	—	19	19	14	5	10
1964	—	—	—	—	—	18	61	24	6	0
1965	18	1	17	7	8	54	14	9	5	50
1969	−5	8	6	5	−6	29	17	3	0	26
1978	5	−25	5	19	19	46	102	39	−1	6
Mean	7	−12	19	49	37	36	39	18	10	28
% (h)	0.7	11.8	1.6	6.5	6.3	1.9	3.0	1.2	1.1	1.5
					Mean total phosphorus: inorganic plus zooplankton					
	1007	90	1177	798	628	1958	1324	1494	927	1391

* In g-at P-sec.
** Transport north is negative, south positive.
† Transport east (in) is positive, west (out) negative.
†† Sum of transports into (+) or out of (−) area shown in Figure 1.
ND No data.
a No PO_4 available for station 70.55, values at station 70.60 used as an approximation.
b PO_4 values from line 83.
c Station 80.90 and 110.90 interpolated
d No station 110.90 data, value underestimates transport south.
e No station 110.80 or 110.90 data, value underestimates transport south.
f Some PO_4 to 150 m only, missing values to 200 m obtained from 1950-78 mean
g Some PO_4 to 100 m only, missing values to 200 m obtained from 1950-78 mean
h Percent of P transport contributed by zooplankton P.

probably fortuitous, considering the approximations in all the calculations, but it is clear that Ekman transport can help account for net input due to geostrophic flow.

Several cruises show large departures from the mean net budget that do not seem related to seasonal differences alone. This is not surprising, however, considering observational and analytical problems in geostrophic calculations (see "Methods"). Because of the small number of observations, and their limitations, the magnitude of variations in flow (Table 3) suggests that little significance can be placed on any but the largest differences in between-cruise P transport. We do not try to quantify that variability or to test for statistically significant differences. Despite data limitations, mean 1950-78 mass balances are quite close to zero (Table 2). In our data set we cannot separate signal (i.e., actual cruise-to-cruise and year-to-year variations) from noise (i.e., random errors due to measurement or other analytical errors). However, other studies have shown that flow of the California Current is extremely variable on many spatial and temporal scales (e.g., Sette and Isaacs 1960; Owen 1980; Chelton 1980), and much variation in our calculated flow is probably real. As a result, much of the variation in P transport is also likely to be real (see "Discussion").

Table 3 presents (1) north-south P transport (PO_4 + zooplankton P) across lines 70, 80, and 110; (2) east-west transport for the four winters and six summers; (3) net P budgets for the area by cruise; and (4) overall seasonal means for transports and budgets for both PO_4 and zooplankton P.

Table 4 shows mean P transports and budgets for 1950 through 1978. These data were derived from mean PO_4 data (Figure 2) and mean geostrophic velocity data (Figure 3).

DISCUSSION

The range in PO_4 concentration at a depth within the upper 200 m (Figure 2) is about a factor of 2 to 3, with greater ranges in the nutricline and at all depths near the coast (because of upwelling). Water fluxes vary by factors of 100 or more, and are negative in many cases. As a result, the first-order cause of variation in

TABLE 4
Phosphorus Transport Using All Phosphate and Geostrophic Velocity Data from 1950 to 1978*

	Inorganic dissolved phosphate	Zooplankton phosphorus	Total	Percent zooplankton
Winter				
Line 70	−130	−8	−138	6.2
Line 80	−510	3	−507	0.6
Line 110	869	6	875	0.7
West edge	704	16	720	2.3
Net budget	−295	2	−293	0.7
Summer				
Line 70	1216	26	1242	2.1
Line 80	883	34	917	3.9
Line 110	1829	13	1842	0.7
West edge	1017	8	1025	0.8
Net budget	404	21	425	5.2

*in g-at P/sec. Sign notation as in Table 3.

P transport and budgets is variation in advection, not changes in concentration of PO_4.

Large between-year, within-season variability in P transport (e.g., compare winters of 1965 and 1969 for line 70, or summers of 1964 and 1965 for line 110) suggests that, data problems aside, the changes are real. Some contributing factors are week-to-month variability caused by eddies (e.g., Owen 1980) and quasi-random turbulence of length scales similar to the sampling grid (75 x 75 - 225 km). Large-scale (current-wide) interannual variations in current strength also contribute (Wickett 1967; Saur 1972; Chelton 1980, 1981; Bernal and McGowan 1981).

Smaller-scale fluctuations in flow driving short-term variations in P transport can be seen clearly in geostrophic flow contours for cruises 5007, 6107, and 6407 (see Wyllie 1966, Charts 42, 142, 155). While long-term mean flows are generally southerly across all lines everywhere except near the coast (Figure 3), even our limited data set showed that net northerly flow could occur between station pairs anywhere from the coast out to station 90, on any line, in either season. Flow across the western edge also varied in direction, depending on mesoscale physical structure. Such variations have strong effects on net transport across entire lines and thus on P budgets. A northerly flow at some point on a line of stations may be only one side of an eddy carried on a more generalized southerly flow; we are unable to resolve this, and our budgets use the numbers with their calculated signs.

P transport and budgets for single cruises (i.e., small time and space scales) are very sensitive to these unresolved problems. This makes it difficult to quantify long-term interannual variations caused by current-wide variations in transport, and we have not attempted to do so. We did look qualitatively at possible consequences of long-term changes in advection of P on interannual, current-wide zooplankton fluctuations. Those fluctuations were identified by Bernal (1979) and shown to be correlated with advection (Bernal and McGowan 1981; Bernal 1981; Chelton 1981). Bernal (1979) identified several anomalous zooplankton biomass periods between 1959 and 1969; only two (in 1950 and 1964) coincide with our P data. In addition, Chelton and Bernal identified 1978 as an anomalous year (Chelton 1980, 1981). In both summer and winter of these three years—1950, 1964, 1978—we find no obvious relation between P transport across lines and anomalous zooplankton biomasses. Neither do we find a relation between total P budgets and biomasses. Clearly, more detailed data will be needed to detect correlations, on time scales of years, that must exist between plant nutrient supply and primary or secondary productivity.

Bernal and McGowan (1981) and Bernal (1981) also showed that between 1950 and 1969 interannual fluctuations of zooplankton biomass about the long-term mean were not correlated with deviations from long-term means of Bakun's (1973) upwelling index. Because of our limited data set, we were able to look only at correlations between P transport during individual cruises and corresponding upwelling indices. Magnitudes of P transport across lines 70, 80, and 110 were ranked within seasons. Kendall's rank difference correlation coefficients (r_d; Tate and Clelland 1957) were determined for the relationship of these rankings to upwelling indices at nearby points (Figure 1). Indices for the same month or the one or two months preceding were used, depending on distance of the line from the point where upwelling indices were calculated. There is no significant correlation ($p>0.20$) (Table 5) of variations in P transport across lines with variations in upwelling index. We also calculated correlation coefficients between transport across line 70 and upwelling indices off Washington (45°N, 125°W) with lags of 0 to 2 months. Again, no significant ($p>0.20$) correlations were found.

Because variations in near-surface PO_4 concentrations for individual cruises could reflect variations in upwelling intensity, we also calculated r_d between upwelling indices and integrated P (0-50 m) at the two stations nearest the coast on lines 70, 80, and 110. No significant correlations (all $p>0.20$) were found.

Tables 3 and 4 show that P transports across lines are generally greater in summer than winter, although there is considerable variability in individual cruise data (Table 3). The 1950-78 mean P transports also show a net northward flux of P across lines 70 and 80 during winter (Table 4); this is evident in only a few individual cruises. The seasonal difference could be

TABLE 5
Transport of Inorganic Dissolved Phosphorus* across CalCOFI Lines 70, 80, and 110 during Individual Cruises Compared to Upwelling Indices at Four Stations before or during those Cruises

Line 70					Line 80				Line 110					
		Upwelling Index					Upwelling Index				Upwelling index			
PO_4 Transport	Station:[a] Time:[b]	A t-1	A t-2	B t=0	PO_4 Transport	Station: Time:	B t-1	C t-1	PO_4 Transport	Station: Time:	C t-1	C t-2	D t=0	D t-1
1184		24	11	3	−311		35	42	1577		42	9	58	60
2781		−11	−5	7	988		10	36	2194		36	19	44	73
−291		−8	−39	−1	946		−3	4	766		4	6	45	8
325		−49	14	−36	−1217		−10	−5	93		−5	37	9	13
	r_d =	0.0	0.20	0.82		r_d =	0.40	0.40		r_d =	0.80	−0.20	0.40	0.80
1002		121	210	115	1311		153	191	—		—	—	—	—
2461		102	75	134	1627		139	241	1959		241	351	94	158
2035		149	140	313	2300		296	515	3261		515	469	176	204
3076		230	300	228	592		280	322	97		322	295	95	142
1079		145	112	303	1062		245	377	951		377	353	219	194
1878		233	289	252	815		240	306	1114		306	195	184	224
	r_d =	0.20	0.17	0.09		r_d =	−.09	0.09		r_d =	0.10	0.50	−0.20	0.35

* g-at P/sec
a See Figure 1 for locations.
b Same month as transport calculation t = 0.
month previous to transport calculation t-1.
two months previous to transport calculation t-2.
c 1977-78 upwelling indices from National Marine Fisheries Service, La Jolla, courtesy Paul Smith.
r_d = Kendall rank difference correlation coefficient; in all cases, $P_{(r_d)} > 0.20$.

due to increased advection across lines during summer (Table 2) and to increased PO_4 concentration at all depths (0-500 m) over most of the study area. Table 6 summarizes 178 comparisons of summer and winter mean PO_4 values at standard depths by line and station: summer values exceed winter values 147 times. This is a highly significant difference ($p<<0.01$, H_0: $\phi = 0.50$, binomial distribution, Tate and Clelland 1957). Similarly, integrated PO_4 (mg-at P/m^2) to 75 m and 500 m were generally higher in summer than in winter (Table 7). The higher summer integrated PO_4 values may be due to shoaling of isopycnals during this season (Eber 1977). The shoaling brings colder water with higher nutrients up to within the depth range used for our calculations of integrated PO_4.

Net P budgets for the area reflect seasonal differences in P transport: summer P import is greater than winter for mean budgets of individual cruises (Table 3), and there is summer import but winter export of P in 1950-78 mean seasonal budgets (Table 4). Given

TABLE 6
Comparison of Summer vs. Winter Phosphate Concentrations at Standard Depths from 0 to 500 m. Using Station Means, 1950-78*

	Line 70			Line 80			Line 110		
Station	S>W	S<W	S=W	S>W	S<W	S=W	S>W	S<W	S=W
35							7	3	0
40							9	1	0
50					Coastline		10	0	0
52		Coastline		9†	0	0	NS	NS	NS
53	9	1	0	NS	NS	NS	NS	NS	NS
55	NS	NS	NS	9	1	0	NS	NS	NS
60	5	4	1	10	0	0	10	0	0
70	9	0	1	9	0	1	9	1	0
80	10	0	0	10	0	0	7	3	0
90	2	7	1	7	3	0	6†	2	1
	35	12	3	54	4	1	58	10	1
			Totals N = 178	S>W 147	S<W 26	S=W 5			

NS No station.
* E.g., for line 70, station 53, at 9 of 10 standard depths, the mean summer PO_4 concentration was greater than the winter concentration.
† No 500 m PO_4.

TABLE 7
Winter and Summer Water Column Phosphate (mg-at P/m²) Integrated to 75 m and 500 m

	Line 70				Line 80				Line 110			
	Winter		Summer		Winter		Summer		Winter		Summer	
Station	75 m	500 m	75 m	500 m	75 m	500 m	75 m	500 m	75 m	500 m	75 m	500 m
35									52	1029	65	1052
40									37	996	59	1041
50						Coastline			31	905	43	1061
52		Coastline			82	658▽	146	750▽ 1072*	NS	NS	NS	NS
53	99	1125	116	1148	NS	NS	NS	NS	NS	NS	NS	NS
55	ID	ID	116	1185	77	1062	121	1171	NS	NS	NS	NS
60	79	1114	91	1108	71	1074	90	1123	36	928	51	1066
70	66	1058	79	1099	49	974	79	1137	35	920	43	950
80	46	957	67	1051	47	946	56	1042	29	911	34	901
90	49	966	46	949	44	876	40	952	33⁺	115	37	118⁺
S>W	0-75 m	4 ex 5	P<0.20		5 ex 6		P<0.10		7 ex 7		P<0.05	
	0-500 m	3 ex 5	P>0.20		6 ex 6		P≈0.05		6 ex 7		P≈0.05	

ID Insufficient data
NS No station
\+ to 150 m only
▽ to 200 m only
* to 500 m

the small number and high variability of the data sets, the potential biases, and limitations due to analytical problems, seasonal differences in both P transports and net budgets are probably not significant. The most conservative interpretation is that, over the long term, the study area is neither a source nor sink of PO_4. The decrease in total PO_4 in the upper layers of the California Current from north to south (Reid 1962; Owen 1974) (especially in summer: Table 7) may be due to one or both of the following: (1) input (above 200 m) of high PO_4 water from the north and low PO_4 water from the west balanced by output of a relatively large volume of low PO_4 water to the south across line 110; (2) the possible mass imbalance for water above 200 m (Table 2), suggesting a net subsidence of PO_4-rich water out of the bottom of the area. Regardless of the long-term P balance, variability in net P budget occurs both within and between individual years and should have a marked effect on productivity of the California Current.

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