# SEASONALITY OF CHLOROPHYLL CONCENTRATIONS IN THE CALIFORNIA CURRENT: A COMPARISON OF TWO METHODS

GIULIETTA S. FARGION
Department of Marine Biology
Texas A & M University
P.O. Box 1675
Galveston, Texas 77553

JOHN A. MCGOWAN
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0228

ROBERT H. STEWART
Department of Oceanography — 3146
Texas A & M University
College Station, Texas 77843

## ABSTRACT

We have compared estimates of seasonal variations in chlorophyll concentrations in the California Current as derived from a large series of *in situ*, water-column, measures and from the Coastal Zone Color Scanner–West Coast Time Series (WCTS) in both original and corrected forms. We find substantial differences between the two methods, satellite and *in situ*. The original WCTS showed winter to be the peak season for pigment concentration everywhere, but the *in situ* data did not. A previous study of the corrected WCTS data found "a strong seasonal cycle with a spring summer maximum," but the *in situ* data contained no convincing evidence for a "strong" cycle when all of the data were examined. Some individual years (e.g., 1984) do have clear spring maxima, particularly very near shore, but most do not. There are extensive interannual variations.

The overall relation between surface *in situ* (or 0–20 m) pigment concentrations and integrated, *in situ* water-column (0–150 m) concentrations is very uncertain in terms of mean concentrations per unit volume, spatial heterogeneity, and temporal change.

## RESUMEN

Comparamos estimaciones de la variación estacional de clorofila en la Corriente de California: observaciones *in situ* (en la columna de agua, datos provenientes de una gran serie de datos) y observaciones de la Serie de Tiempo de la Costa Oeste ("WCTS") obtenidas con el Sensor a Color de la Zona Costera (series "corregida" y "original"). Encontramos diferencias substanciales entre los dos métodos, *in situ* y por satélite. La serie WCTS original mostró un máximo en la concentración de pigmentos en invierno (en todos los sitios), pero no así los datos *in situ*. Un estudio anterior de la serie WCTS corregida encontró "un ciclo estacional pronunciado con un máximo en primavera-verano"; sin embargo, al examinar todas las observaciones *in situ*, los datos no mostraron evidencia convincente de un ciclo "pronunciado". Algunos años (por ejemplo 1984) mostraron claramente máximos en primavera, particularmente muy cerca a la costa, pero la mayoría no. Hubo gran variabilidad interanual.

Considerando todas las observaciones, la relación entre las concentraciones de pigmento superficiales (o de 0 a 20 m) *in situ* y las concentraciones integradas *in situ* en la columna de agua (0 a 150 m) son muy inciertas en cuanto a las concentraciones medias por unidad de volumen, heterogeneidad espacial y cambio temporal.

## INTRODUCTION

One of the most well known and recognizable changes in the environment is seasonality. Any method used to study change (in time and space) should be able to detect a seasonal signal, if it occurs and if it is strong with respect to changes on other frequencies.

Because the ocean and its populations vary considerably on many time-space scales, there are many opportunities for sampling error. In addition, when indirect or remote methods are used, measurement error may become a serious problem. In practice, both sources of error are usually present, but some methods may suffer from one source more than the other. The nature of the error from either source is often difficult to determine. It is useful then, to compare two quite different methods to assess the extent of their agreement. If there is substantial agreement, then we may have some (limited) assurance that our understanding of change is reasonably good in spite of not knowing the exact nature of the errors.

The following study is a comparison between a large series of *in situ* measurements of chlorophyll and those made remotely by the Coastal Zone Color Scanner (CZCS) in the California Current. The larger question is: What is the seasonal change? But the immediate question, treated here, is: How do the two methods compare?

Measurements spanning forty years have shown clear and unambiguous seasonal changes in the physical structure and mass transport of the California Current system (Reid et al. 1958; Eber 1977; Hickey 1979; Lynn et al. 1982; Chelton and Davis

1982; Jackson 1986; Reid 1987; Lynn and Simpson 1987; and many others). This seasonal variation may be sharply differentiated from variations on other frequencies (Chelton 1984). Although the entire physical system has a strong seasonal component to its variability, many authors also define three spatial domains: oceanic, coastal, and a large zone between these. This "in-between" zone is centered about 200–300 km offshore, parallels the coast, and is considered to be the "core," or main body, of the California Current. The flow is equatorward and is strongest in spring and summer; off Baja California it bends inward towards the coast. In the coastal zone there is a strong poleward counterflow, especially in fall and winter. This counterflow weakens in the spring. South of Point Conception it appears as a large, geographically fixed cyclonic eddy over the shallow offshore banks in the Southern California Bight (Lynn and Simpson 1987). Thus the seasonal patterns of water movement inshore in the coastal zone and in the main body of the current, especially south of Point Conception, are not the same. These differences have led to somewhat different areal, seasonal patterns and ranges of the local temperature and density structure (Lynn and Simpson 1987). These features show up in the long-term means; thus they are not transient or vague.

Relatively fewer studies of biological seasonality in this system have been based on such large data sets. But in spite of very large interannual variations, Smith (1971), Colebrook (1977), Chelton et al. (1982), and McGowan (1985) have shown that mean macrozooplankton biomass changes seasonally in all sectors. Once again, however, there are nearshore-offshore, north of Point Conception–south of Point Conception differences in the patterns of seasonality. In all sectors summer is the maximum and winter the minimum, but the offshore waters have a greatly damped cycle (Bernal and McGowan 1981), as do the sectors off Baja California (Chelton et al. 1982).

If these systematic, seasonal patterns in zooplankton biomass result from local trophodynamics or from the transfer of energy from *in situ* primary production, we might expect a spring or early summer productivity maximum of phytoplankton and perhaps a phytoplankton biomass bloom. This expectation may also come from the application of the Sverdrup critical depth model for the initiation of the spring bloom (Sverdrup 1953). This model depends strongly on the depth of light penetration (deeper with increasing sun angles, as in the spring) and changes in the depth of vertical mixing which, in turn, depends on the degree of vertical density stratification (i.e., warming of the upper layer, as in the spring). This model assumes that nutrients are not limiting, and predicts only the onset of the spring bloom. Smetacek and Passow (1990) have reviewed the frequent misuse of this model but conclude that in its original form it is "logically sound." They suggest that the model be limited to a period of stabilization of a shallow layer long enough to permit algal growth rates to exceed the death rates due to grazing. Whether the original version, the misinterpreted version, or the Smetacek-Passow version is used, this model predicts a late spring–early summer bloom of phytoplankton in the California Current, because that is when the stability maximum shoals in all zones and intensifies in the nearshore (Lynn et al. 1982).

Are there studies to validate these two independent predictions (zooplankton bloom and Sverdrup model), both of which agree on the seasonal timing of the phytoplankton bloom, namely late spring? The assumption behind both predictors is that local, rather than horizontal, advective processes are responsible.

Quite different kinds of measurements are available to test these predictions. Direct *in situ* water-column measurements of chlorophyll have been made by the Southern California Bight Study (SCBS) group (Carlucci et al. 1986). In the lexicon of Lynn, Simpson, Reid, Jackson, etc. the SCBS area is not in the "main body" of the California Current but rather in the coastal domain of the southern California borderland, often called the Southern California Bight. Eppley et al. (1985) have reviewed the SCBS measurements and conclude that the chlorophyll concentrations ". . . exhibit a significant seasonal variation," being lowest in summer and highest in winter. Mullin (1986), on the other hand, using the same data, could detect no seasonal signal in chlorophyll or primary production. In the very nearshore, at the Scripps Institution of Oceanography pier, spring appears to be the time of maximum diatom and dinoflagellate abundance (Allen 1941; Tont 1989).

Much additional *in situ* data come from the California Cooperative Fisheries Investigations (CalCOFI), which have measured water-column chlorophyll concentrations at a large number of stations in the main body of the California Current and the bight since 1969.

A second method of assessing how plant biomass changes in time and space is by studying remotely sensed concentrations of plant pigments as measured by the Coastal Zone Color Scanner (Smith and Baker 1982; Eppley et al. 1985; Peláez and McGowan

1986; Abbott and Zion 1987; Balch et al. 1989). Using 129 images from the West Coast Time Series (WCTS; Abbott and Zion 1985) for the period from 1979 to 1981, Michaelsen et al. (1988) studied seasonal variability of "pigment biomass" in a series of "boxes" of about 10,000 km$^2$ each, selected to represent areas both onshore and offshore north of Point Conception, in the Southern California Bight, and south of San Diego. Their "nearshore" areas were centered about 150 km off the coast in what they call the "mainflow" of the California Current; the "offshore" areas were 300 km away from the coast in what they called "oceanic water." They also used the SCBS, shipboard data (i.e., *in situ* water-column measurements) from the "inner portion" of the Southern California Bight, but "only those observations obtained from stations at least 10 km from the coast." These data were used for comparison with the satellite data. Michaelsen et al. found that "Annual cycles in upper layer chlorophyll," as measured by either satellite or ship, show winter maxima and summer minima, but the "total" (i.e., in the entire water-column) "as measured from ships, on the other hand, peaks in early summer." They attribute this to the seasonal development of "strong sub-surface maxima and surface minima." They clearly imply that these "shipboard" observations and their interpretations apply throughout the entire study area even though the measurements came only from the "inner portion" of the Southern California Bight.

Strub et al. (1990) studied seasonality of satellite-derived surface pigment concentration over a much larger area of the California Current. They too used the West Coast Time Series of satellite data to determine seasonal patterns. However, they identify an error in the processing of these data where the single-scattering Rayleigh algorithm that was used produces winter values "known" to be too high (no citation given). They point out that the symptoms of this sort of error should be "uniformly increasing chlorophyll with latitude with a seasonal maximum in winter." This point was also made by Gordon et al. (1988), who implied that the algorithm should be valid for solar zenith angles less than 50°–55°, which corresponds to latitudes of 26.5°–31.5° in late December. Thomas and Strub (1990) state "The algorithm used to correct these images for atmospheric (Rayleigh) scattering is known to produce artificially high values of pigment concentrations in regions of high zenith angle. This pigment concentration estimated by the CZCS at high latitudes during winter cannot be trusted." They nevertheless used values up to a latitude of 47°N, which has a solar zenith angle of around 70° in late December; we will use data as far south as 28°N and as far north as 39°20′.

Although no *in situ* validation of the seasonal change in direction of error or its magnitude is given by Strub et al. (1990) they do suggest an algorithm correction that appears to bring the data into "conformity" with another algorithm (Gordon et al. 1988) and to produce a "strong" seasonal cycle with a spring-summer maximum outside of the Southern California Bight, a northward progression of high pigment concentrations, and — within the bight — low seasonality with a "relative minimum" in late summer. They point out that in regions "where previous work has been done" (presumably the *in situ* studies of Eppley et al. 1985 in the Southern California Bight) "there is general agreement with the seasonal cycles found here."

Thus there is disagreement among authors as to the direction and magnitude of the seasonal changes in plant biomass as measured by chlorophyll content, whether this was measured directly *in situ*, or remotely by satellite. Some of the error of satellite-derived measurements of chlorophyll in the California Current has been addressed by Balch et al. (1989), who used *in situ* measurements. But they did not report a seasonal change in the direction of error, as did Strub et al. (1990). Although Gordon et al. (1988) adjusted the algorithm used to process the original WCTS data, and Strub et al. (1990) introduced their own correction, there remain the issues of what the extensive *in situ* CalCOFI data say about how well this correction depicts seasonality in areas outside of the Southern California Bight and what a more extensive data set (CalCOFI plus SCBS) says about it within the bight. Neither the Gordon et al. (1988) nor Strub et al. (1990) "corrections" have been validated against seasonal *in situ* chlorophyll data.

Further, there are the very nearshore areas (less than 10 km) to consider. These are of some concern because here is where people have their most intimate contact with the ocean, where pollutants are discharged, and where society, in general, is most concerned with "changes." We have some right to expect that the tempo and mode of phytoplankton population biology here differs from the offshore (Allen 1941), and that this observation needs to be validated with more modern data in order to compare with satellite-derived information. Although there are recognized potential errors in remotely sensed pigment estimates from very nearshore pixels (class II error, Gordon and Morel 1983), these too need validation from *in situ* data. The immediate nearshore zone is too important to ignore. We also will test the idea that the error is greatest at higher latitudes.

## METHODS

We began our study (Fargion 1989) before becoming aware of the ongoing work of Michaelsen et al. (1988), Strub et al. (1990), or Thomas and Strub (1990), and yet we treated the WCTS data similarly. We too examined the seasonal, remotely sensed, signal in a set of "boxes" both nearshore and offshore, north and south in the California Current, as did Michaelsen et al. (1988). Thus our results can be compared to theirs. We also tried to determine the larger-scale, satellite-derived, seasonal signal from the WCTS, as did Strub et al. (1990). We differ from these studies in that we also examined the very nearshore satellite signal where we had a relatively extensive high-frequency time series of chlorophyll measurements (over 1000) and where the water column is almost always well mixed. We also differ in that we used the very extensive CalCOFI time/space series of over 958 *in situ* water-column chlorophyll measurements (12 to 14 depths each) for areas both within the bight and well outside of it to validate the remote sensing data. The years covered by these 58 cruises are 1969, 1972, 1978, and 1983 through 1991. These measurements are particularly apt because they may be directly related to the extensive hydrographic and biological studies of the California Current cited earlier.

The satellite scenes and numerical values are from the Nimbus 7 Coastal Zone Color Scanner and were processed to gridded and earth-navigated images of nearsurface pigment concentrations by Mark Abbott and Philip Zion. The processed images were provided by the NASA Ocean Data System of the Jet Propulsion Laboratory. We used these satellite data at three different spatial scales (one of which was rather large), so it was important to select relatively cloud-free, large, individual images. Between the years 1979 and 1985 we found 190 suitable images. We used no spatial composite images.

We first determined the seasonal cycle of satellite-derived color from the WCTS at nearshore, midstream, and offshore locales (1 × 1 mosaic pixels 7.1 km on a side) nearest to CalCOFI oceanographic stations 60, 80, and 110 on seven CalCOFI lines from 40°N to 30°N, a distance of some 1080 km (figures 1 and 2). We then selected six smaller areas, or "boxes," similar to those of Michaelsen et al. (1988). These were 162 km by 162 km and represented the nearshore and offshore regimes off San Francisco, Point Conception, and San Diego (figure 3). We space-averaged the numerical data from within each of these boxes for each of the available monthly images (figure 4). Thus this aspect of our study resembles that of Michaelsen et al. (1988).

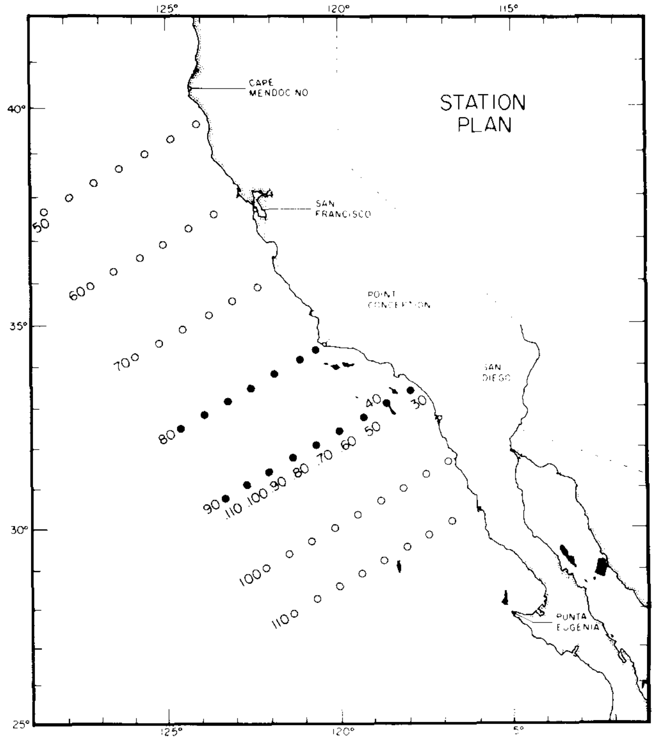


Figure 1. The pattern of CalCOFI stations used in this study. The *open circles* are stations on cardinal lines 50 through 110 and are the locales for the seasonal satellite study shown in figure 2. The *closed circles* on cardinal lines 80 and 90 are the locations of the *in situ* chlorophyll measurements shown in figures 6, 7, 9, and 10. Stations are numbered .50 through .120. For example, the nearest station to the shore on line 90 is station 90.50; the farthest offshore is 90.110.

Finally we looked at the satellite monthly means from 1979 to 1985 from a single pixel nearest the end of the ocean pier at Scripps Institution. This was in order to compare the satellite results with a high-frequency (paired samples, two times per week), long-term (six years) time series of chlorophyll measurements taken here. This latter part of our study has the additional benefit of introducing a different system, the very nearshore (class II) environment, into the comparison of satellite with *in situ* results — a system in which we have a large background of information and where the water column is very shallow and almost always very well mixed (figure 5).

The data from Scripps Pier resulted from filtration and extraction of paired 50-ml samples taken just beneath the surface. Our other more oceanic water column data come exclusively from the SCBS and CalCOFI programs. Both of these used the same extraction and analysis procedures and are

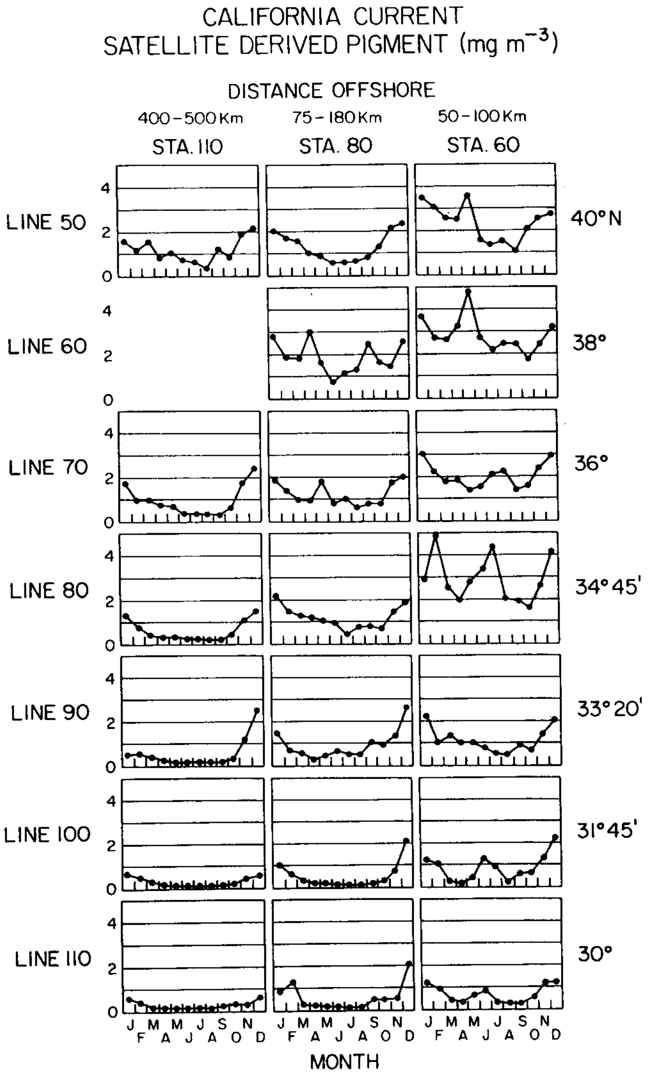


Figure 2. Satellite-derived (uncorrected WCTS) estimates of chlorophyll concentrations. These are averaged from 1 × 1 mosaics (7.1 km on a side) nearest to CalCOFI stations offshore .110, mid-current .80, and nearshore .60, on seven cardinal lines between 40°N and 30°N (see figure 1).

identical with the Scripps Pier procedures (Venrick and Hayward 1984).

## RESULTS

### *Satellite-Derived Pigment Seasonality*

Our large-scale study of the original, uncorrected, 1988 WCTS data show essentially what Strub et al. (1990) have suggested about the sense of the error. That is, in the nearshore (the sta. 60 N-S line) and in midstream (the sta. 80 N-S line) chlorophyll generally increases from south to north. Offshore (the sta. 110 N-S line) this trend is less evident. But because these same north-south trends may be present in some of the larger spatial maps of *in situ* water-column chlorophyll from CalCOFI cruise reports (SIO 1984a,b) and atlases (Owen 1974) it is not quite clear that the observation can be considered to represent an algorithm error or a satellite measurement error. What is evident, however, is that in virtually all of the sectors, most of the WCTS-derived graphs indicate that peak concentrations occur in the winter months of December and January even as far south as 28°N, station 110 on line 110 (figure 2). Offshore and in the Southern California Bight (south of line 80) midsummer generally appears to be the time of minima in WCTS estimates of chlorophyll concentration. Midsummer secondary maxima occur nearshore, north of Point Conception (line 80, figure 2). Thus our satellite determinations of "seasonality" agree with Michaelsen et al. (1988) and with the uncorrected data of Strub et al. (1990) and Thomas and Strub (1990). This suggests that wintertime errors in the satellite algorithm may be important for solar angles as small as 51.5°.

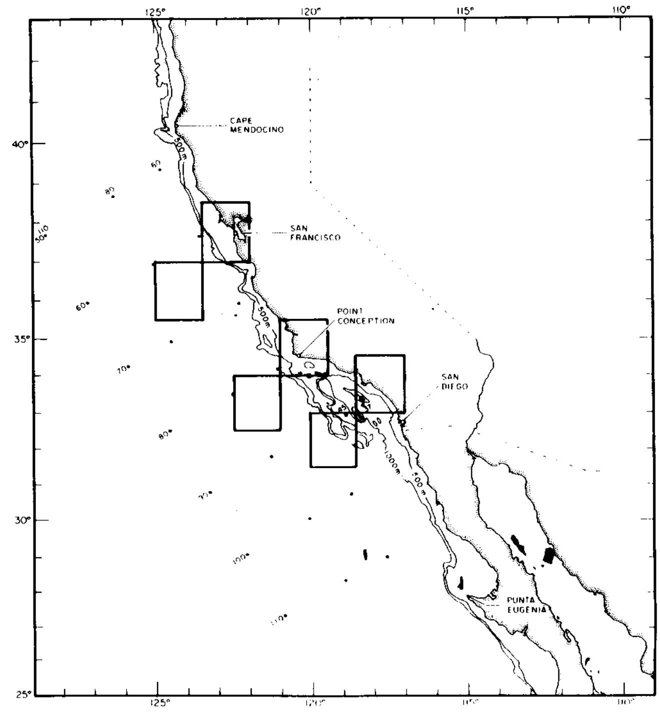


Figure 3. Six "boxes" of 162 km × 162 km where satellite-derived chlorophyll concentrations (uncorrected WCTS) were space-averaged by month for the years 1979 to 1985.

In our study of the boxes, for which a large amount of space-time averaging was done, the seasonal trends provided by WCTS do not differ strongly from the above (figure 4), in spite of the spatial smoothing. Here again we see winter maxima everywhere, and midsummer minima in the offshore and in the San Diego inshore boxes. Secondary summer highs are present in the inshore Point Conception and San Francisco sectors. The

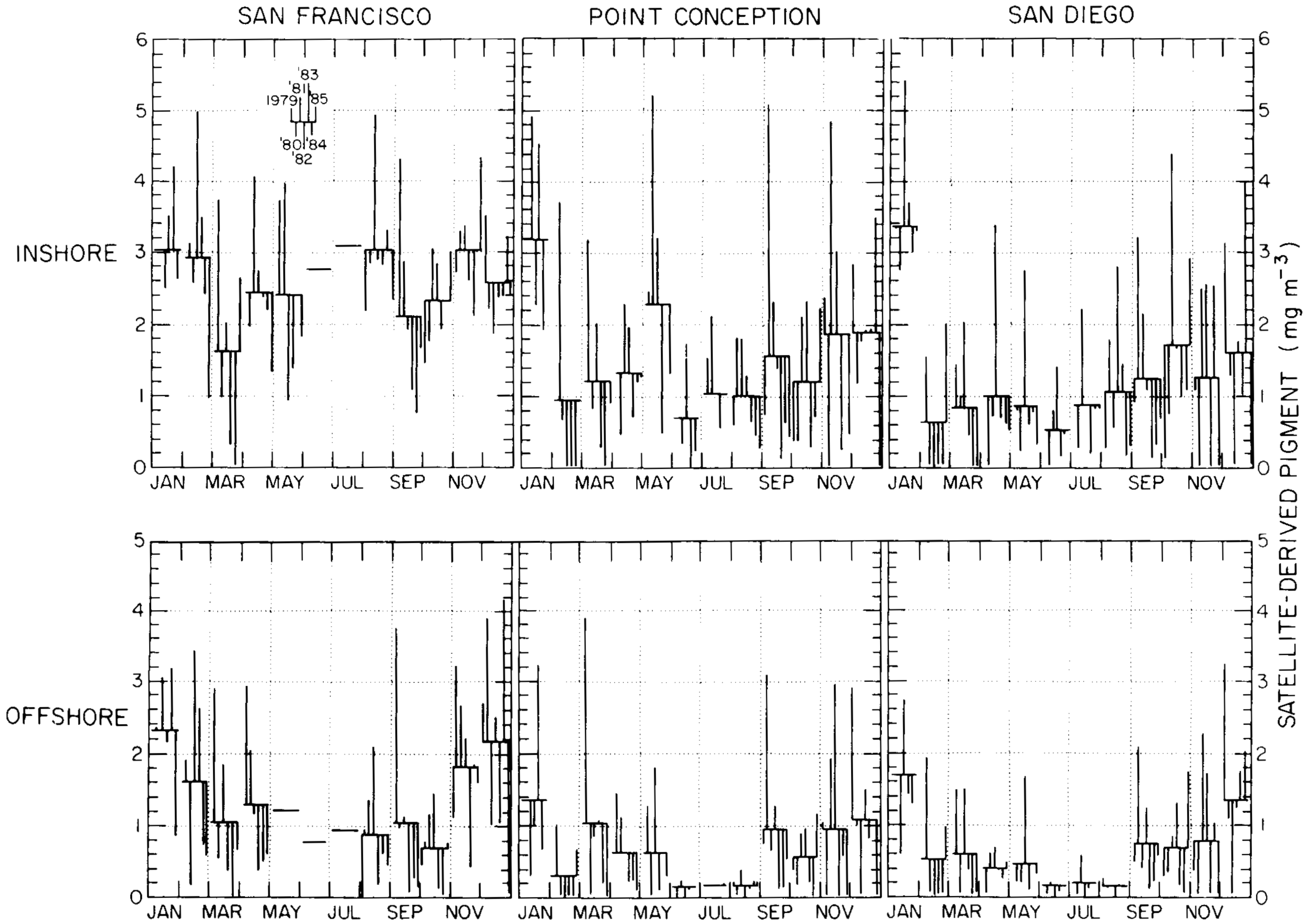


Figure 4. Monthly means of chlorophyll estimates (mg/m³) in the six boxes shown in figure 3. The *horizonal bars* are the overall monthly means; the *vertical bars* are the monthly values from individual years (uncorrected WCTS).

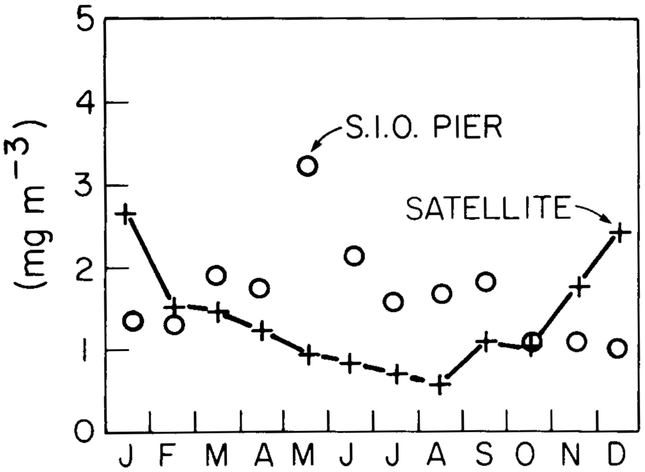


Figure 5. *Circles*, the concentrations by month of surface chlorophyll plus phaeopigments (mg/m³) from twice-weekly sample pairs from Scripps Pier (1983–85). *Crosses*, satellite-derived (uncorrected WCTS) estimates from the nearest pixel.

major new aspect in this part of our study is the large interannual signal seen in all six sectors.

Finally we examined the mean seasonal signal from a pixel nearest the Scripps Pier (figure 5). Here there is a clear winter (Dec.–Jan.) maximum and a midsummer (Jul.–Aug.) minimum in the WCTS, satellite-derived estimates. So far we are in total agreement with Strub et al. (1990), who first mentioned this important error in the open scientific literature: that the uncorrected (as of 1990) WCTS showed strong, regular, winter blooms of phytoplankton in the California Current.

### *Satellite*–In Situ *Comparisons*

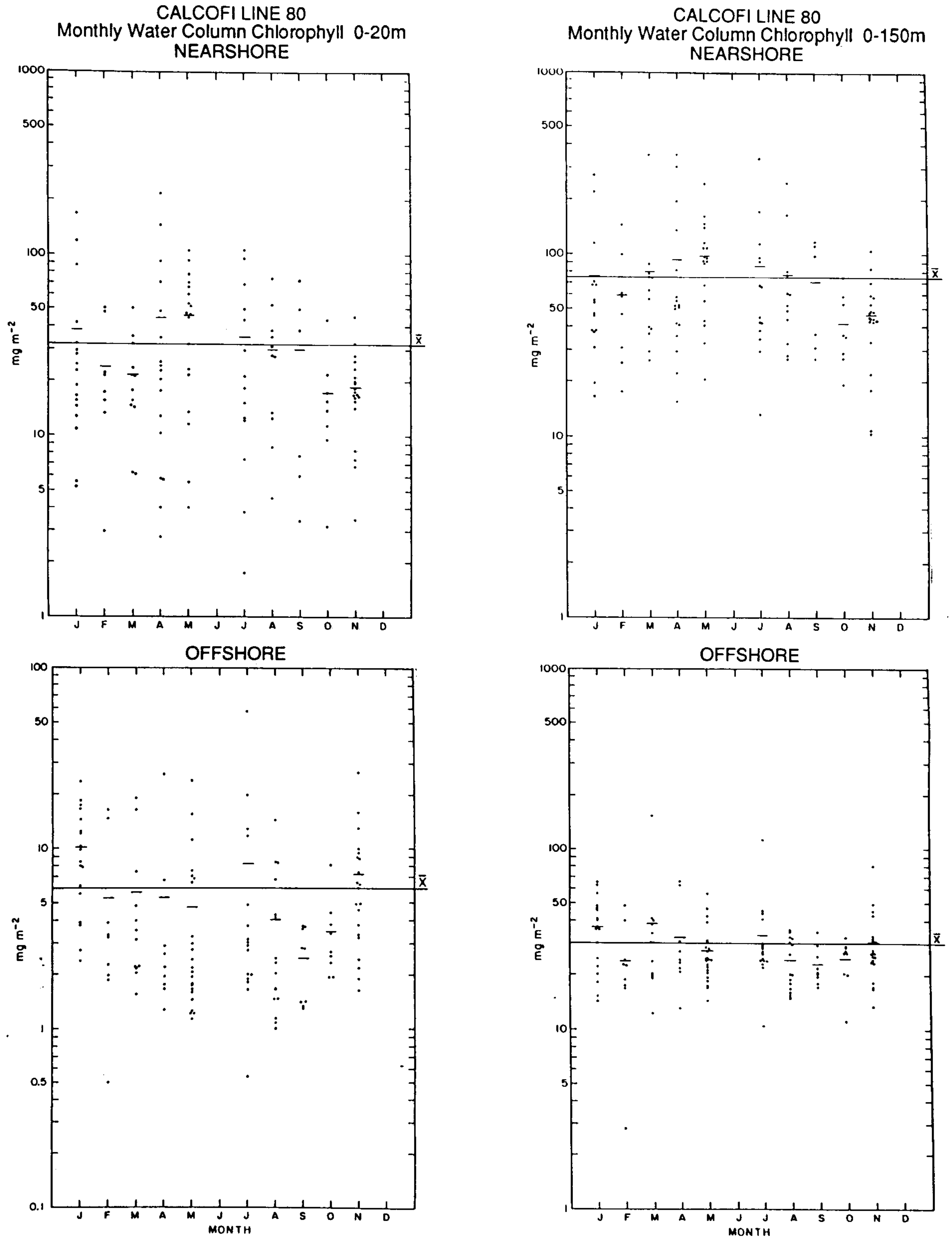
In the following sections we will show extensive *in situ* water-column data. These contain no evidence for winter peaks in the concentrations of chlorophyll anywhere in the California Current. We will also examine how surface *in situ* or 0–20-m *in situ* estimates of chlorophyll abundance relate to complete (0–150-m) water-column measurements and will show that their patterns of change in space and time do not agree. Note that where there is a well-developed mixed layer, changes in surface chlorophyll should reflect changes in 0–20-m integrated chlorophyll abundance. That is the depth range generally thought to be well represented by CZCS color measurements.

There are too few large-scale surveys of the chlorophyll content of all the sectors of the California Current, particularly in the north, so we cannot map large-scale spatial, seasonal changes with great confidence, especially because of aliasing by other frequencies. The few seasonal maps that do exist (Owen 1974) do not confirm the broad-scale WCTS, satellite estimates of the seasonal directions of change. But we do have more extensive water column data from farther south on CalCOFI lines 80 and 90 (figure 1) and from the bight, especially during the time that the CZCS operated. We can look for the nearshore-offshore seasonal signals off of Point Conception, well south of it, and in a large amount of space-averaged data from the combined SCBS-CalCOFI time series within the bight.

CalCOFI line 80 runs normal to the coastline and transects our two Point Conception boxes and those of Michaelsen et al. (1988) (figure 1). The means of integrated, (0–150 m) water-column chlorophyll from stations in the inner 120 km of this line show only a weak "seasonal" peak in April-May means, with a minimum in the fall season. It is evident that there are large variations about these monthly means and that some springs have much less chlorophyll than some winters (figure 6 and table 1). Offshore on this line the overall mean concentration decreases considerably; there are broadly overlapping standard deviations (table 1); and there is no convincing evidence for a regular seasonal cycle. As with the nearshore data, the nonseasonal variations are large. If one integrates only through the upper 20 m in an attempt to emulate the optical depths over which the radiometer in the CZCS is thought to accurately estimate chlorophyll pigment concentration, a seasonal picture is even less evident (figure 6). Over this depth range there is still no strong seasonal signal, but the May mean is the maximum and the October the minimum. These two means differ significantly

TABLE 1
**Monthly Means, Medians, Ranges, Standard Deviations, and Coefficients of Variability, Nearshore (<Sta. 70) and Offshore (Sta. 70 and Greater) for the Near-Surface (0–20 m) and Water-Column (0–150) *In Situ* Chlorophyll Measurements (mg m$^{-2}$) on CalCOFI Line 80, 1969–91**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nearshore 0–20 m | | | | | | | | | | | | |
| Mean mgm$^{-2}$ | 38.38 | 23.99 | 21.58 | 44.77 | 46.28 | | 35.01 | 29.75 | 29.68 | 17.07 | 18.69 | |
| SD | 44.71 | 17.01 | 12.65 | 58.34 | 29.79 | | 34.31 | 20.73 | 28.52 | 12.25 | 9.59 | |
| N | 17 | 8 | 12 | 17 | 18 | 0 | 14 | 11 | 6 | 8 | 20 | 0 |
| MD | 24.73 | 19.25 | 19.55 | 24.32 | 45.30 | | 19.76 | 28.00 | 23.00 | 14.70 | 17.20 | |
| MIN | 5.25 | 2.96 | 6.11 | 2.75 | 4.03 | | 1.74 | 4.55 | 3.40 | 3.19 | 3.47 | |
| MAX | 168.80 | 51.51 | 50.38 | 218.39 | 105.16 | | 108.14 | 74.45 | 72.60 | 44.16 | 45.95 | |
| SD/$\bar{x}$ | 1.16 | 0.71 | 0.59 | 1.30 | 0.64 | | 0.98 | 0.70 | 0.96 | 0.72 | 0.51 | |
| Nearshore 0–150 m | | | | | | | | | | | | |
| Mean mgm$^{-2}$ | 74.63 | 59.06 | 79.30 | 91.98 | 96.39 | | 84.46 | 76.54 | 69.51 | 41.50 | 46.43 | |
| SD | 71.27 | 41.24 | 87.16 | 98.25 | 53.58 | | 83.05 | 64.97 | 42.73 | 18.69 | 22.71 | |
| N | 16 | 8 | 12 | 17 | 18 | 0 | 14 | 12 | 6 | 8 | 20 | 0 |
| MD | 50.85 | 52.39 | 60.07 | 52.60 | 92.20 | | 55.71 | 56.30 | 66.66 | 35.83 | 44.71 | |
| MIN | 16.57 | 17.48 | 26.13 | 15.46 | 20.33 | | 13.08 | 26.58 | 26.57 | 18.98 | 10.49 | |
| MAX | 271.82 | 143.06 | 348.30 | 350.85 | 241.64 | | 335.53 | 248.08 | 116.80 | 73.99 | 104.11 | |
| SD/$\bar{x}$ | 0.95 | 0.70 | 1.10 | 1.07 | 0.56 | | 0.98 | 0.85 | 0.61 | 0.45 | 0.49 | |
| Offshore 0–20 m | | | | | | | | | | | | |
| Mean mgm$^{-2}$ | 10.14 | 5.34 | 5.70 | 5.19 | 4.72 | | 8.22 | 4.03 | 2.43 | 3.46 | 7.17 | |
| SD | 5.90 | 5.90 | 5.85 | 7.86 | 5.51 | | 14.01 | 3.79 | 1.07 | 1.93 | 5.74 | |
| N | 18 | 9 | 12 | 9 | 23 | 0 | 16 | 15 | 9 | 9 | 21 | 0 |
| MD | 9.19 | 3.20 | 3.32 | 2.20 | 2.16 | | 2.95 | 2.30 | 2.76 | 2.65 | 5.98 | |
| MIN | 2.38 | 0.50 | 1.55 | 1.27 | 1.14 | | 0.54 | 1.00 | 1.30 | 1.91 | 1.62 | |
| MAX | 23.17 | 16.36 | 18.99 | 25.70 | 23.77 | | 56.93 | 14.20 | 3.70 | 8.06 | 26.22 | |
| SD/$\bar{x}$ | 0.58 | 1.10 | 1.03 | 1.51 | 1.17 | | 1.70 | 0.94 | 0.44 | 0.55 | 0.80 | |
| Offshore 0–150 m | | | | | | | | | | | | |
| Mean mgm$^{-2}$ | 37.48 | 24.20 | 39.18 | 32.89 | 27.74 | | 33.89 | 24.47 | 23.38 | 25.01 | 30.82 | |
| SD | 16.18 | 13.70 | 37.95 | 19.40 | 10.49 | | 23.06 | 7.72 | 5.78 | 6.44 | 14.79 | |
| N | 18 | 9 | 12 | 9 | 23 | 0 | 16 | 15 | 9 | 9 | 21 | 0 |
| MD | 36.92 | 22.84 | 30.53 | 24.87 | 24.57 | | 26.73 | 20.75 | 21.13 | 26.87 | 26.90 | |
| MIN | 14.63 | 2.89 | 12.52 | 13.19 | 14.88 | | 10.68 | 15.30 | 17.68 | 11.39 | 13.86 | |
| MAX | 67.43 | 49.85 | 155.96 | 68.05 | 57.80 | | 113.51 | 36.19 | 35.17 | 32.89 | 81.25 | |
| SD/$\bar{x}$ | 0.43 | 0.57 | 0.97 | 0.59 | 0.38 | | 0.68 | 0.32 | 0.25 | 0.26 | 0.48 | |


CALCOFI LINE 80
Monthly Water Column Chlorophyll 0-20m
NEARSHORE

CALCOFI LINE 80
Monthly Water Column Chlorophyll 0-150m
NEARSHORE

OFFSHORE

OFFSHORE

Figure 6. Integrated *in situ* water-column measurements of chlorophyll on cardinal line 80. There are three "nearshore" and three to six "offshore" stations. Station 70 (see figure 1) was taken as the breakpoint between nearshore and offshore. Each *dot* represents the integral of either depths over 0–20 m or depths over 0–150 m. *Horizontal bars* are long-term monthly means. Data are from 1969, 1972, 1978, and 1984–91.

TABLE 2

**Monthly Means, Medians, Ranges, Standard Deviations, and Coefficients of Variability, Nearshore (<Sta. 70) and Offshore (Sta. 70 and Greater) for the Near-Surface (0–20 m) and Water-Column (0–150) *In Situ* Chlorophyll Measurements (mg m$^{-2}$) on CalCOFI Line 90, 1969–91**

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nearshore 0–20 m | | | | | | | | | | | | |
| Mean mgm$^{-2}$ | 12.43 | 10.62 | 13.26 | 17.38 | 15.76 | 9.75 | 9.96 | 10.24 | 7.24 | 6.35 | 5.10 | 6.69 |
| SD | 8.47 | 7.75 | 25.90 | 23.45 | 18.87 | 7.27 | 12.44 | 13.20 | 11.31 | 6.94 | 3.79 | 4.21 |
| N | 44 | 35 | 43 | 48 | 56 | 14 | 38 | 36 | 27 | 36 | 48 | 15 |
| MD | 9.68 | 8.70 | 6.88 | 8.74 | 9.06 | 7.62 | 5.41 | 4.58 | 2.95 | 3.52 | 4.07 | 4.48 |
| MIN | 2.05 | 2.03 | 2.07 | 2.19 | 1.53 | 1.90 | 1.90 | 1.85 | 2.05 | 1.91 | 1.00 | 2.60 |
| MAX | 30.66 | 36.14 | 165.95 | 94.05 | 111.40 | 25.72 | 65.86 | 51.41 | 52.40 | 38.22 | 25.10 | 17.08 |
| SD/$\bar{x}$ | 0.68 | 0.71 | 1.95 | 1.35 | 1.20 | 0.75 | 1.25 | 1.29 | 1.56 | 1.09 | 0.74 | 0.63 |
| Nearshore 0–150 m | | | | | | | | | | | | |
| Mean mgm$^{-2}$ | 37.51 | 39.09 | 42.31 | 56.09 | 50.13 | 37.23 | 48.87 | 35.74 | 35.57 | 33.51 | 29.45 | 30.04 |
| SD | 12.05 | 15.97 | 27.42 | 47.94 | 34.58 | 17.64 | 42.38 | 17.77 | 12.40 | 20.09 | 9.02 | 11.84 |
| N | 42 | 34 | 42 | 48 | 56 | 14 | 37 | 37 | 26 | 35 | 48 | 15 |
| MD | 35.95 | 33.35 | 35.09 | 35.27 | 37.70 | 31.11 | 34.96 | 29.90 | 31.39 | 26.98 | 27.78 | 27.81 |
| MIN | 14.19 | 21.43 | 20.94 | 22.15 | 17.93 | 17.06 | 12.90 | 14.44 | 21.60 | 8.19 | 10.52 | 13.96 |
| MAX | 64.75 | 82.76 | 184.31 | 233.25 | 199.98 | 75.32 | 203.75 | 101.63 | 74.07 | 116.37 | 61.59 | 50.53 |
| SD/$\bar{x}$ | 0.32 | 0.41 | 0.65 | 0.85 | 0.69 | 0.47 | 0.87 | 0.50 | 0.35 | 0.60 | 0.31 | 0.39 |
| Offshore 0–20 m | | | | | | | | | | | | |
| Mean mgm$^{-2}$ | 4.24 | 2.78 | 3.13 | 3.79 | 2.61 | 9.67 | 2.44 | 1.67 | 1.80 | 1.80 | 2.57 | 4.04 |
| SD | 2.75 | 2.04 | 3.17 | 6.49 | 2.81 | 3.86 | 2.12 | 1.25 | 1.40 | 0.68 | 1.72 | 1.03 |
| N | 40 | 23 | 30 | 28 | 35 | 5 | 27 | 24 | 12 | 19 | 33 | 7 |
| MD | 3.26 | 1.99 | 2.05 | 2.05 | 1.60 | 8.09 | 1.82 | 1.30 | 1.42 | 1.89 | 1.95 | 3.89 |
| MIN | 1.16 | 1.05 | 0.84 | 1.00 | 0.93 | 6.36 | 0.31 | 0.14 | 1.00 | 0.40 | 1.04 | 2.88 |
| MAX | 12.41 | 8.07 | 13.45 | 26.25 | 15.10 | 16.00 | 10.89 | 6.34 | 6.05 | 2.71 | 9.44 | 5.83 |
| SD/$\bar{x}$ | 0.65 | 0.73 | 1.01 | 1.71 | 1.08 | 0.40 | 0.87 | 0.75 | 0.78 | 0.38 | 0.67 | 0.25 |
| Offshore 0–150 m | | | | | | | | | | | | |
| Mean mgm$^{-2}$ | 25.58 | 22.58 | 23.36 | 31.97 | 26.66 | 37.03 | 33.66 | 20.53 | 21.36 | 24.61 | 22.51 | 23.15 |
| SD | 9.44 | 8.69 | 8.20 | 22.47 | 11.92 | 8.62 | 44.68 | 6.65 | 4.41 | 4.27 | 5.24 | 3.99 |
| N | 37 | 15 | 29 | 28 | 32 | 5 | 25 | 22 | 12 | 12 | 31 | 7 |
| MD | 23.44 | 20.34 | 22.20 | 26.29 | 22.92 | 37.60 | 26.01 | 18.86 | 19.90 | 23.16 | 21.84 | 23.24 |
| MIN | 14.02 | 13.53 | 14.87 | 17.19 | 12.20 | 25.58 | 5.40 | 8.40 | 15.84 | 19.47 | 15.91 | 17.07 |
| MAX | 61.16 | 48.20 | 49.38 | 109.02 | 61.18 | 48.67 | 245.43 | 39.00 | 30.93 | 33.90 | 39.83 | 27.80 |
| SD/$\bar{x}$ | 0.37 | 0.38 | 0.35 | 0.70 | 0.45 | 0.23 | 1.33 | 0.32 | 0.21 | 0.17 | 0.23 | 0.17 |

($p <.05$). There are even fewer reasons to claim an offshore 0–20-m water-column seasonal signal (figure 6, table 1).

Farther south, along CalCOFI line 90 (figure 7 and table 2) we have done a similar study. The "nearshore" stations are within the bight, and the "offshore" stations are in the main body of the California Current. The median and mean values of integrated, (0–150) water-column chlorophyll within the bight on this transect show some evidence of a seasonal signal, with the April-May means well above the overall mean. A test of the April, May, and June means against those of December, January, and February, with the null hypothesis of "no difference" was rejected ($p < .005$). But the very broad scatter of points and the large standard deviations indicate a strong nonseasonal component to the variability. Again the offshore data are even less seasonal, and a similar test with an identical null hypothesis could not be rejected. If, as with the more northerly stations on line 80, we integrate through only the upper 20 m, we see that the monthly scatter of points increases greatly, making it even more difficult to detect a regular seasonal pattern, and making it quite clear that variations on frequencies other than seasonal are very large (figure 7, table 2). Inspection of both figures reveals that many of these monthly means are skewed upwards by a few very high outliers. These outliers do, however, tend to fall between March and September. Perhaps it is only in this sense that we can see an occasional "strong" seasonal cycle with a "spring-summer" maximum (Strub et al. 1990; Thomas and Strub 1990).

Because the line 90 data present such an indeterminate picture, we used the combined CalCOFI-SCBS data to space-average by month over the entire bight in the hope that averaging a larger number of stations here ($n$ = 700) would reduce some of the ambiguity. But neither the monthly, bightwide, space-averaged, integrated chlorophyll nor the surface, space-averaged data showed a clear seasonal pattern (figure 8).

Finally we examined the six-year, twice-weekly measurements from Scripps Pier for the presence of a seasonal signal, and compared it to the nearest pixel satellite data (figure 5). Although this locale is

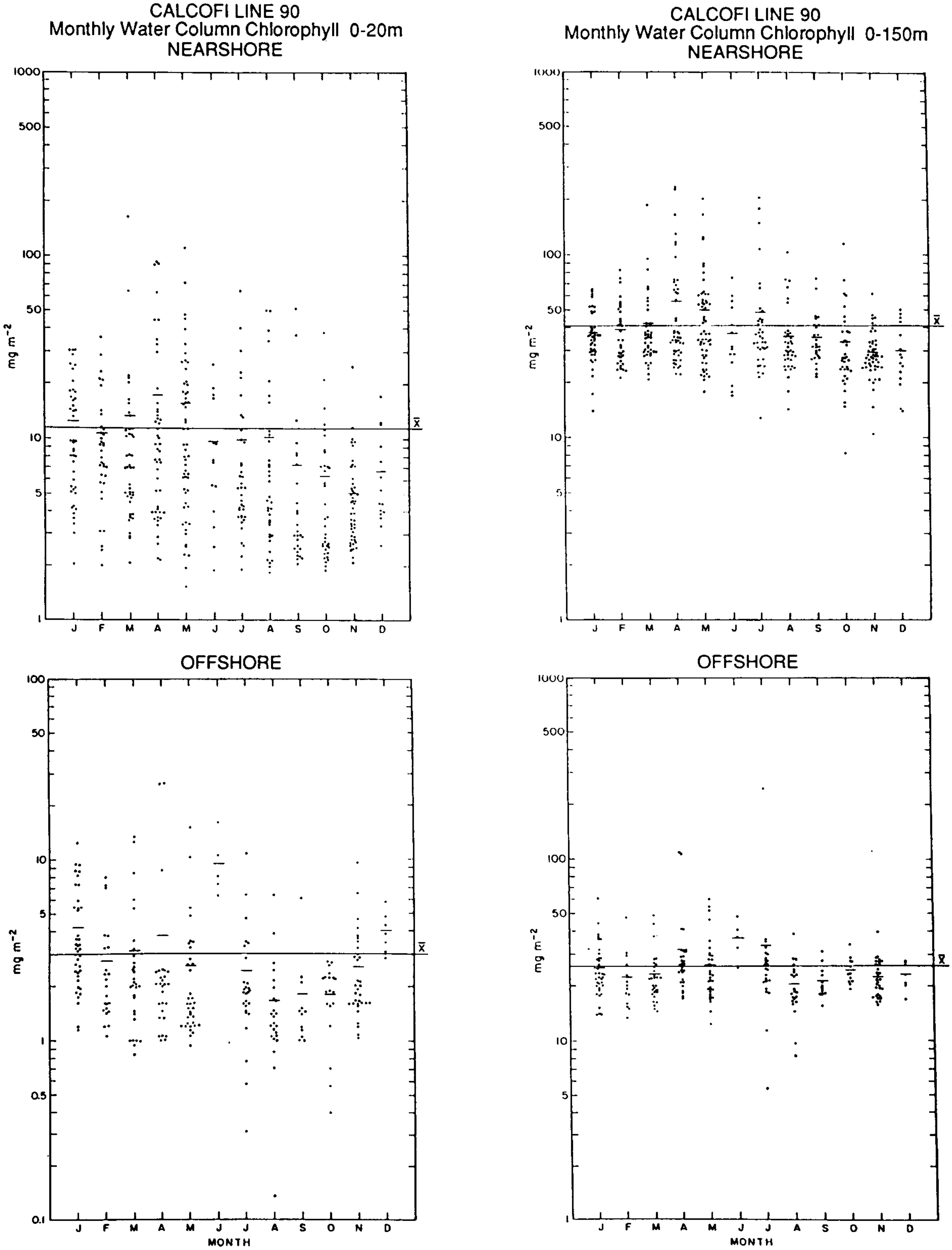


Figure 7. Integrated *in situ* water-column measurements of chlorophyll on cardinal line 90. There are from five to ten "nearshore" and six (except in 1983) offshore stations. Each *dot* represents the integral of either 3 depths over 0–20 m or 12 depths over 0–150 m. *Horizontal bars* are the monthly means. Data are from 1969, 1972, 1978, and 1983–91.

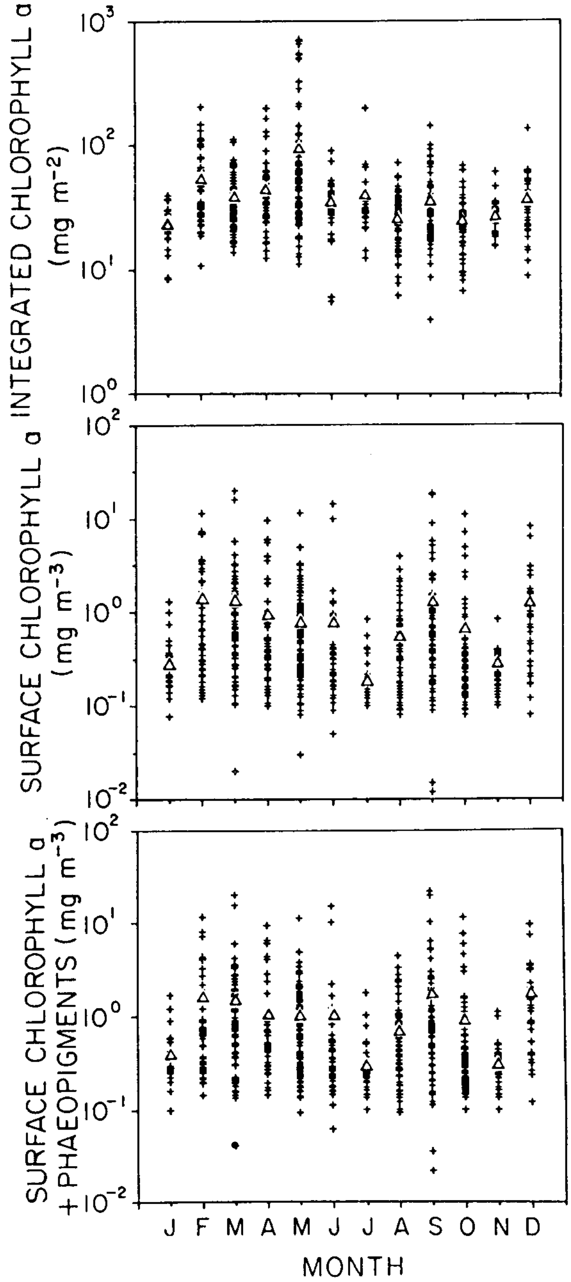


Figure 8. Integrated chlorophyll to the 1% light level, surface chlorophyll, and surface chlorophyll plus phaeopigments. These data are from SCBS (1974–87) and CalCOFI (1969–86) measurements taken in the Southern California Bight. *Triangles* are monthly means.

very nearshore and the satellite data may suffer from the class II sediment interference problem (Gordon and Morel 1983), cell counts and chlorophyll from simultaneous sampling indicate that this may not be a serious source of error (Reid et al. 1985). Further, sediment input from runoff at this locale is very small, episodic, and limited to the winter months. Here there was an evident seasonal maximum, May-June, in the *in situ* data, and although this maximum is due mainly to one particular year it does agree with previous studies of phytoplankton species abundance at this locale (Allen 1941; Tont 1989). Unfortunately the uncorrected satellite data are in broad disagreement. Not only are the satellite winter values large overestimates as compared to the *in situ* data, but the May-June means are underestimates by factors of two or three.

The Strub et al. (1990) and Thomas and Strub (1990) studies of seasonality of phytoplankton pigment concentrations in the California Current did not use winter data because it was "unreliable" or "suspect." In spite of that they conclude that north of the Ensenada Front at about 32°N (Peláez and McGowan 1986) and "outside" of the Southern California Bight there is a "strong" seasonal cycle with a spring-summer maximum. We have already shown there is only a very ill-defined seasonal cycle nearshore in either depth range (0–20 m or 0–150 m) and none at all offshore (i.e., outside the bight).

To visualize the temporal/spatial changes in the *in situ* data and to compare with satellite imagery, we have contoured about eight years of these *in situ* data of chlorophyll plus phaeopigment, by stations, integrated 0–20 m, from lines 80 and 90 (figures 9 and 10). The first three years of the line 80 data do show either spring (for 2 yrs.) or summer (for 1 yr.) peaks very near shore. In the remaining four years, high values occur most of the year except for autumn. Line 90 data are similar in that the spring or summer peaks occur only in the first three years and are only very near shore. The remaining five years of line 90 data seem to have prolonged, nearshore highs most of the year, again excepting the autumn. The lines 80 and 90 data from 1969, 1972, and 1978 have been treated in an identical way. There are no offshore seasonal signals in any of these data. Nearshore, there are no regular temporal patterns, although 1978 did have four stations with high values in July (out of a total of 29 in the entire data set). Neither line of stations shows a very coherent or consistent cycle of change at the station-70 meridian or at greater distances offshore at any time between 1969 and 1991. It is evident from an examination of these plots that the meridional line along station 70 chosen by Thomas and Strub (1990) to sea truth their corrected WCTS data does not accurately represent the sequence of large temporal changes taking place primarily inshore of this meridional line.

There are clear interannual differences to be seen in all of these *in situ* studies, and both Strub et al. (1990) and Thomas and Strub (1990) have emphasized this. But their failure to use winter data from any of the years they studied makes their observa-

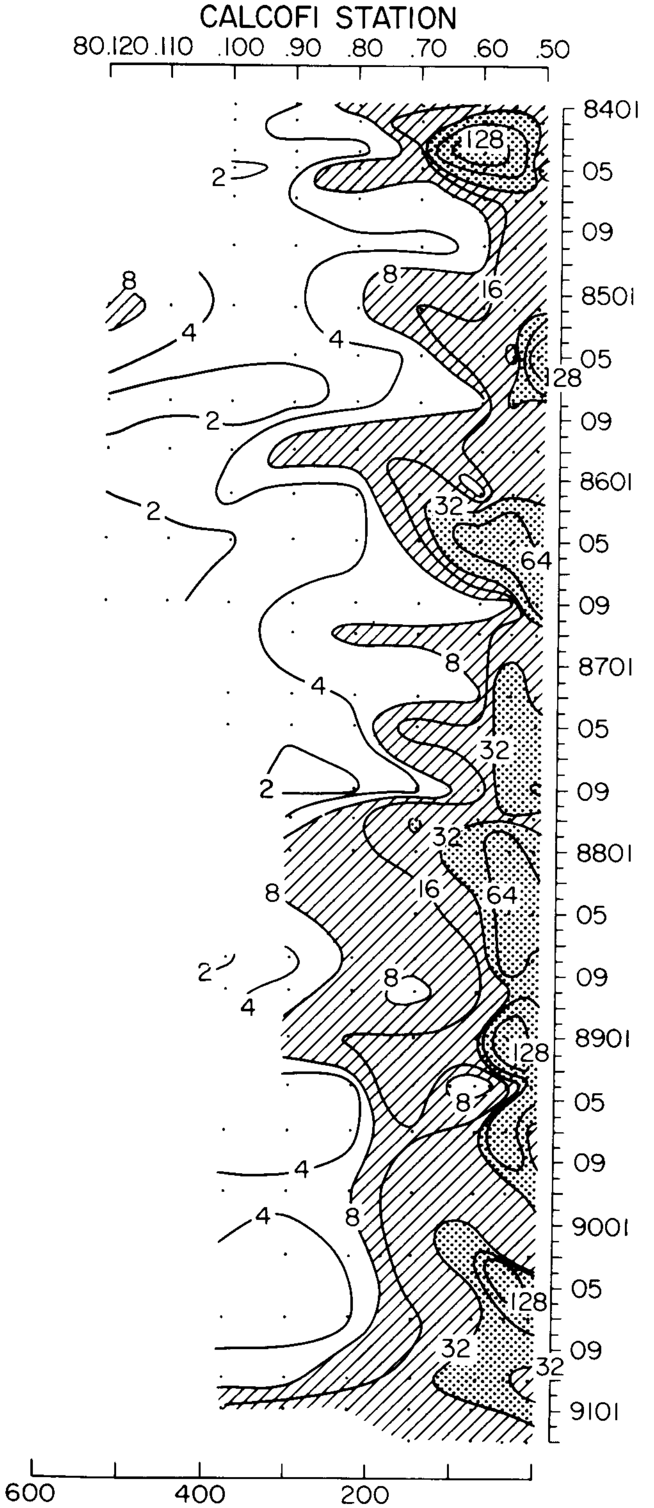


Figure 9. Time-space contours of *in situ* chlorophyll plus phaeopigments integrated over the depth range 0–20 m on CalCOFI line 80. Three samples over this depth range were generally taken.

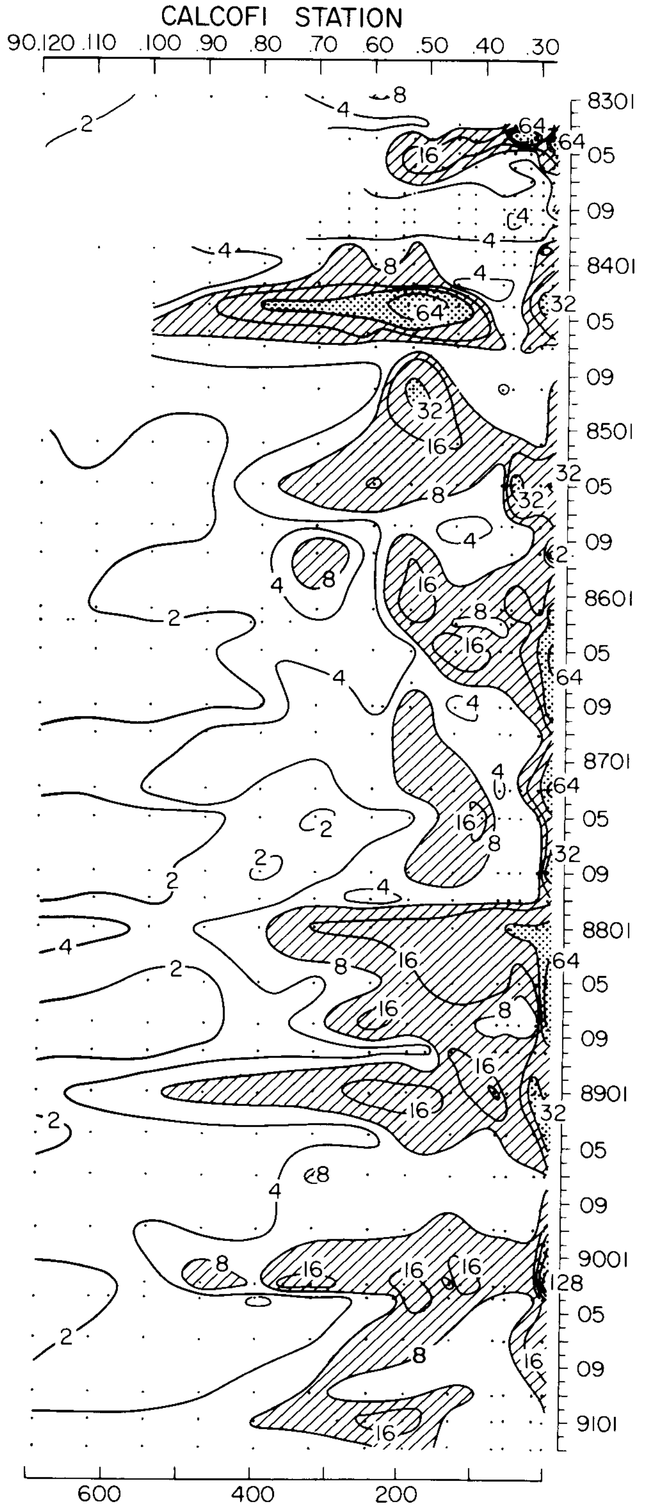


Figure 10. Time-space contours of *in situ* chlorophyll plus phaeopigments integrated over the depth range 0–20 m on CalCOFI line 90. Three samples over this depth range were generally taken.

tions somewhat dubious. Further, the well-known decline in phytoplankton standing crop during the 1983 El Niño (Fiedler 1984; McGowan 1985) accounts for most of their "interannual" changes. Thus the view that there is a "strong seasonal cycle with a spring-summer maximum" outside the bight is not supported by these *in situ* studies; at best the signal is only nearshore, inconsistent, and quite weak.

## CONCLUSIONS

The West Coast Time Series in its original version, based on a single-scattering Rayleigh algorithm, provided data that systematically overestimated winter chlorophyll values in the California Current as compared to our *in situ* data. There is clear evidence from the very near shore that it also underestimated late spring and summer concentrations. This calls into question the results of many previous (before 1990) California Current studies based on these uncorrected WCTS data. The studies are, to an unknown extent, biased because of the strong seasonal error in the data. Strub et al. (1990) attempted to correct the error in the WCTS single-scattering algorithm by assuming that *in situ* chlorophyll values are low and essentially nonseasonal "some" distance from the coast. This assumption may be validated by our *in situ* data, depending on just how far off the coast one looks (figures 9 and 10). Along line 90, chlorophyll values can be substantial even 400 km offshore, and although not seasonal, they certainly vary with time. Strub et al. (1990) derived a correction function dependent on month and latitude, based on their assumption, and subtracted it from the monthly CZCS-WCTS data. They checked this correction against West Coast values from the multiple-scattering "global CZCS" data. They state that this comparison of annual cycles based on the two data sets (corrected WCTS and "global CZCS") indicates that "major conclusions about the March-through-October cycle in the California Current" will not be "changed" when the new WCTS is available. This may very well be true for some researchers, but the fact remains that our extensive *in situ* data provide no convincing evidence for a general summer maximum outside of the Southern California Bight and only weak evidence within the bight itself. The only "strong" *in situ* seasonal mean signal is at Scripps Pier, where May, on average, is high. The magnitude of this peak is due mainly to an unusual red tide in May 1985.

Michaelsen et al. (1988) — in order to explain their results of winter maxima and summer minima in the upper layer, although water column chlorophyll peaks in early summer — have suggested that strong subsurface maxima and surface minima develop during the "spring upwelling season." The satellite radiometer would, in this case, be unable to detect the deep chlorophyll maximum. When we separate our combined CalCOFI-SCBS data into coastal, mid-bight, and outer bight and compare integrated to surface chlorophyll by season (figure 11), we see little support for this hypothesis. There is, however, an onshore-offshore trend in all seasons for surface chlorophyll to be higher in the very near coastal zone (within 10 km) than in mid or outer bight. This is also a consistent feature of all satellite images. There are well-developed, offshore, deep chlorophyll maxima (Venrick et al. 1973), but as yet no extensive study of their changes with time has been made.

Finally, the overall relation between *in situ* measured surface pigments and integrated water-column concentrations is not very useful for predictive purposes (figure 12). Even in winter, where the slope of the regression line is strongly positive, the main body of the data varies by a factor of over 5.

This uncertain relationship is also seen in the 0–20-m *in situ* concentrations and the 0–150-m data (tables 1 and 2; figures 6 and 7) where there is agreement only about half of the time on which months are above the annual mean. Further, the ranges, standard deviations, and coefficients of variability (SD/$\bar{x}$) differ considerably between the two data sets. Even if the satellite did a perfect job of estimating the concentration of chlorophyll in the upper 20 m, it would not be a good estimator of water-column concentrations and their variability, a fact pointed out by Hayward and Venrick (1982) some time ago.

Throughout this paper we have emphasized the lack of correspondence between the satellite determination of space-time patterns and those measured *in situ*. We have implied that the differences are due solely to error in the satellite-derived data. This may not be entirely the case. In their discussion of the sources of error in satellite color data, Chelton and Schlax (1991) point out that small-scale, horizontal heterogeneity is "effectively averaged out by the 1km footprint size of the CZCS." But this averaging out is not the case with our *in situ* measurements. We mentioned earlier that we have observed "outliers" in our data set, particularly during summers. If there are patches of high concentrations that are relatively small and well separated in space, then "outliers" like this can be expected. The question is, have we effectively sampled them? Our cruises were separated in time by quarterly intervals, or greater, and

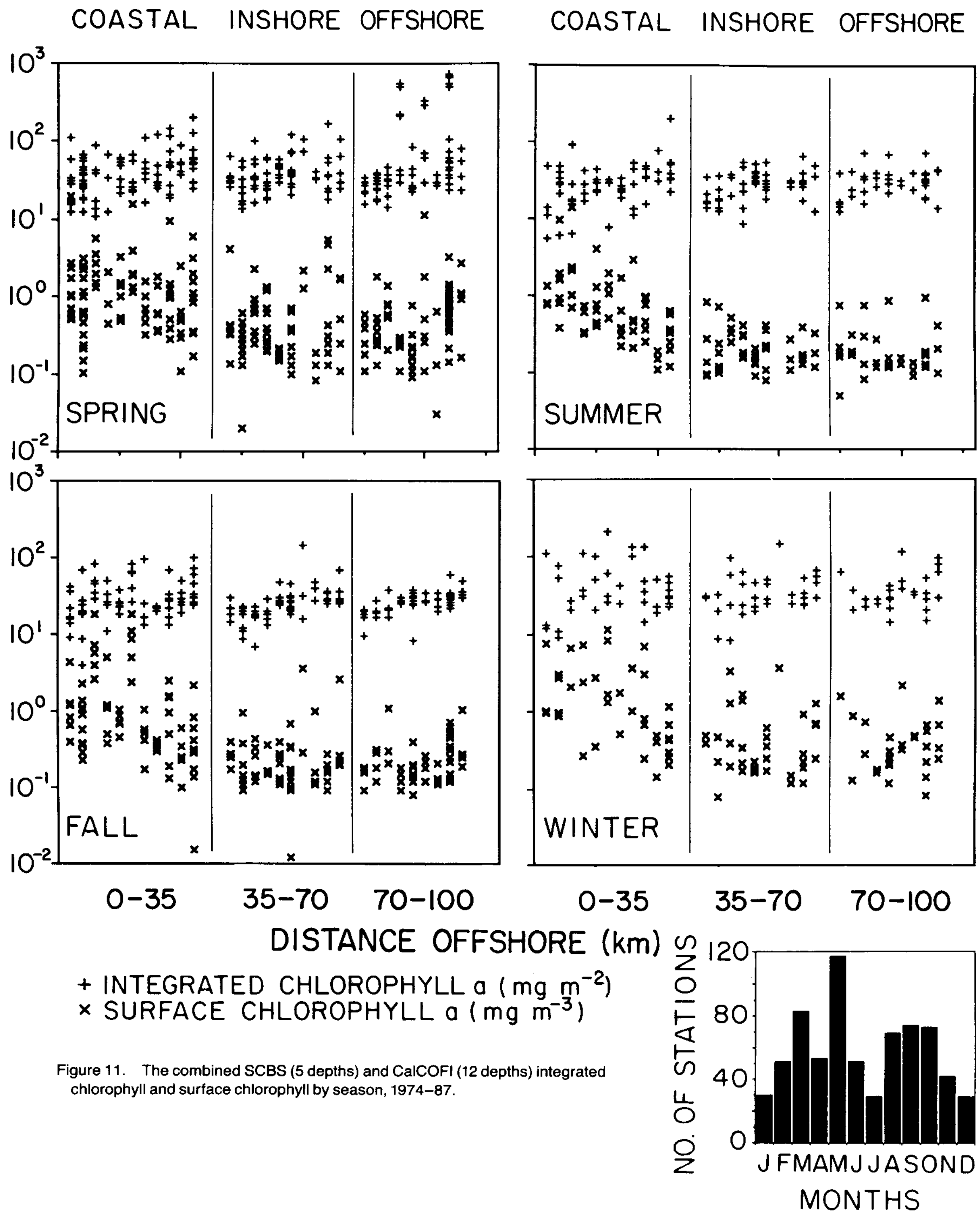


Figure 11. The combined SCBS (5 depths) and CalCOFI (12 depths) integrated chlorophyll and surface chlorophyll by season, 1974–87.

our stations by about 72 km, so there is plenty of opportunity (except in the Scripps Pier data) for aliasing due to high-frequency variability in time and space. Because of this it is possible, but rather unlikely, that we have systematically underestimated the summer *in situ* concentrations. Only a high-frequency, oceanic measurement program carried out for several years, such as the one at Scripps Pier, can give us much insight into this problem.

Satellite remote sensing of phytoplankton biomass is a potentially powerful tool for studying some aspects of oceanic biological systems. But we

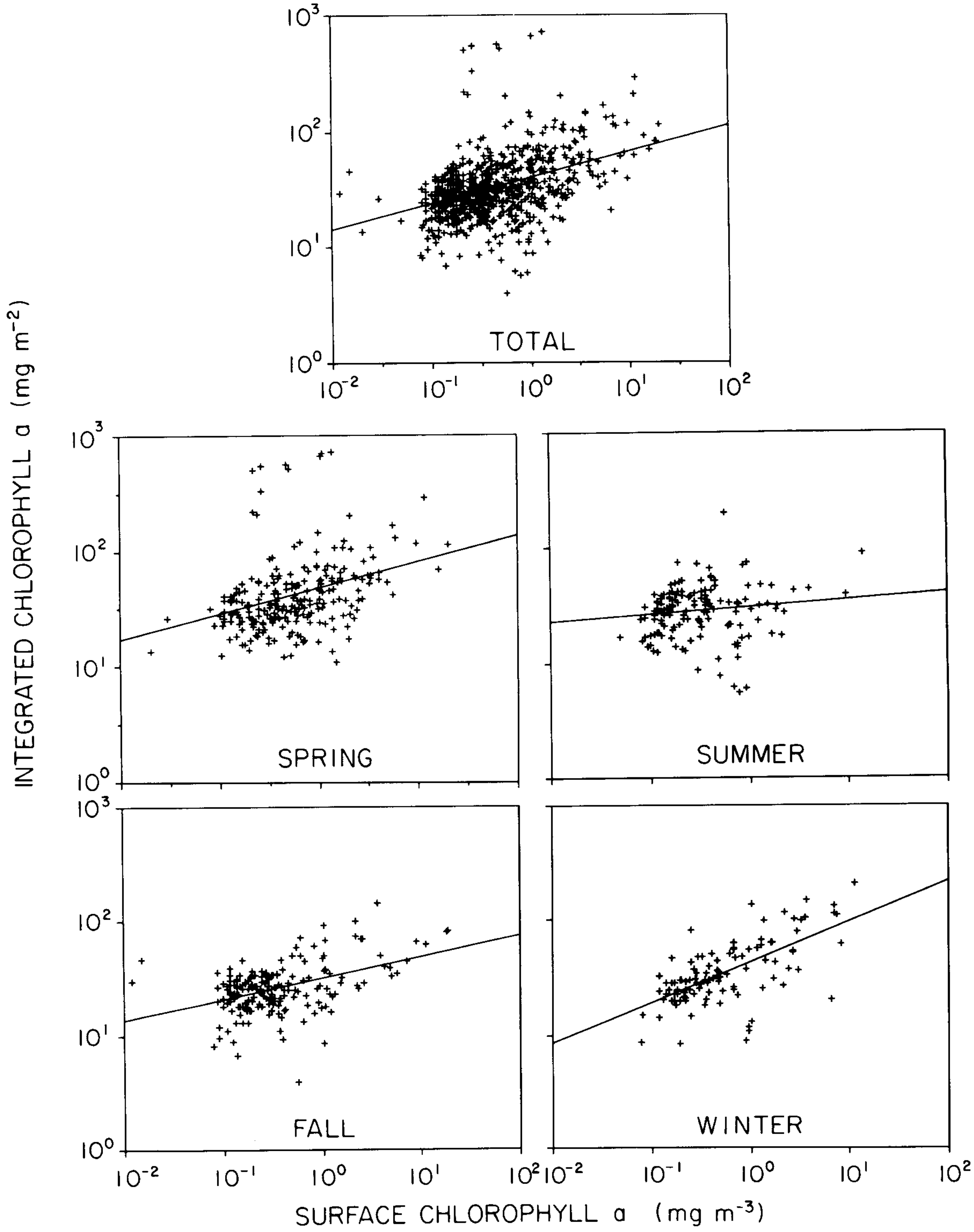


Figure 12. Scatter diagrams of integrated CalCOFI (1969–86) plus SCBS (1974–87) chlorophyll versus surface chlorophyll in the Southern California Bight by season, and overall.

must improve both precision and accuracy if we are to describe and understand the large-scale population biology of phytoplankton from the proxy measurements provided by this tool. Much better ground truthing is called for.

## ACKNOWLEDGMENTS

The *in situ* chlorophyll measurements, made over the years by the CalCOFI and SCBS programs were the work of a number of dedicated marine technicians, and we are indebted to them. The Scripps Pier measurements were made mostly by P. Walker, who also processed the data and originated tables 1 and 2 and figures 6, 7, 9, and 10. We received much good help from the staff at the Jet Propulsion Laboratory, who provided us with the CZCS-WCTS data. We are also grateful to M. M. Mullin and A. Tubbs for their help. This work was supported, in part, by NASA grant NAGW-1237, and in part by the Marine Life Research Group, Scripps Institution of Oceanography, University of California, San Diego.

## LITERATURE CITED

Abbott, M. R., and P. M. Zion. 1985. Satellite observations of phytoplankton variability during an upwelling event. Cont. Shelf Res. 4:661–680.

———. 1987. Spatial and temporal variability of phytoplankton pigment off northern California during Coastal Ocean Dynamics Experiment I. J. Geophys. Res. 92:1745–1756.

Allen, W. E. 1941. Twenty years statistical studies of marine plankton dinoflagellates of southern California. Amer. Midl. Nat. 26:603–635.

Balch, W. M., M. R. Abbott, and R. W. Eppley. 1989. Remote sensing of primary production: I, a comparison of empirical and semi-empirical algorithms. Deep-Sea Res. 36:281–295.

Bernal, P. A., and J. A. McGowan. 1981. Advection and upwelling in the California Current. *In* Coastal upwelling, F. A. Richards, ed. Washington, D.C.: Amer. Geophys. Union, pp. 381–399.

Carlucci, A. F., R. W. Eppley, and J. R. Beers. 1986. Introduction to the Southern California Bight. *In* Plankton dynamics of the Southern California Bight, R. W. Eppley, ed. No. 15 of lecture notes on coastal and estuarine studies. New York: Springer-Verlag, pp. 1–12.

Chelton, D. B. 1984. Seasonal variability of alongshore geostrophic velocity off central California. J. Geophys. Res. 89: 3473–3486.

Chelton, D. B., and R. E. Davis. 1982. Monthly mean sea level variability along the west coast of North America. J. Phys. Oceanogr. 12:757–784.

Chelton, D. B., and M. G. Schlax. 1991. Estimation of time averages from irregularly spaced observations: with application to Coastal Zone Color Scanner estimates of chlorophyll concentration. J. Geophys. Res. 96,C8:14,669–14,692.

Chelton, D. B., P. A. Bernal, and J. A. McGowan. 1982. Large-scale interannual physical and biological interaction in the California Current. J. Mar. Res. 40:1095–1125.

Colebrook, J. M. 1977. Annual fluctuations in biomass of taxonomic groups of zooplankton in the California Current, 1955–1959. Fish. Bull., U.S. 75:357–368.

Eber, L. E. 1977. Contoured depth-time charts (0 to 200 m, 1950 to 1966) of temperature, salinity, oxygen and sigma-t at 23 CalCOFI stations in the California Current. Calif. Coop. Oceanic Fish. Invest. Atlas 25, La Jolla.

Eppley, R. W., E. Stewart, and U. Heyman. 1985. Estimating ocean primary productivity from satellite chlorophyll. Introduction to regional differences and statistics for the Southern California Bight. J. Plankton Res. 7:57–70.

Fargion, G. S. 1989. Physical and biological patterns during El Niño and non–El Niño episodes in the California Current. Ph.D. dissertation, Univ. Calif., San Diego, Scripps Institution of Oceanography.

Fiedler, P. C. 1984. Satellite observations of the 1982–1983 El Niño along the U.S. Pacific coast. Science 224:1251–1254.

Gordon, H. R., and A. Y. Morel. 1983. Remote assessment of ocean color for interpretation of satellite visible imagery; a review. New York: Springer-Verlag, 114 pp.

Gordon, H. R., J. W. Brown, and R. H. Evans. 1988. Exact Rayleigh scattering calculations for use with the Nimbus-7 Coastal Zone Color Scanner. Appl. Opt. 27:862–871.

Hayward, T. L., and E. L. Venrick. 1982. Relation between surface chlorophyll, integrated chlorophyll, and primary production. Mar. Biol. 69:247–252.

Hickey, B. M. 1979. The California Current system — hypotheses and facts. Prog. Oceanogr. 8:191–279.

Jackson, G. A. 1986. Physical oceanography of the Southern California Bight. *In* Plankton dynamics of the Southern California Bight, R. W. Eppley, ed. No. 15 of lecture notes on coastal and estuarine studies. New York: Springer-Verlag, pp. 13–52.

Lynn, R. J., and J. J. Simpson. 1987. The California Current system: the seasonal variability of its physical characteristics. J. Geophys. Res. 92:1294–1296.

Lynn, R. J., K. A. Bliss, and L. E. Eber. 1982. Vertical and horizontal distributions of seasonal mean temperature, salinity, sigma-t, stability, dynamic height, oxygen and oxygen saturation in the California Current, 1950–1978. Calif. Coop. Oceanic Fish. Invest. Atlas 30.

McGowan, J. A. 1985. El Niño 1983 in the Southern California Bight. *In* El Niño North, W. S. Wooster and D. L. Fluharty, eds. Washington Sea Grant Program, Univ. Wash., Seattle.

Michaelsen, J., X. Zhang, and R. C. Smith. 1988. Variability of pigment biomass in the California Current as determined by satellite imagery, 2. Temporal variability. J. Geophys. Res. 93: 10,883–10,896.

Mullin, M. M. 1986. Spatial and temporal scales and patterns. *In* Plankton dynamics of the Southern California Bight, R. W. Eppley, ed. No. 15 of lecture notes on coastal and estuarine studies. New York: Springer-Verlag, pp. 216–265.

Owen, R. W. 1974. Distribution of primary production, plant pigments and secchi depths in the California Current region, 1969. Calif. Coop. Oceanic Fish. Invest. Atlas 20:90–117.

Peláez, J., and J. A. McGowan. 1986. Phytoplankton pigment patterns in the California Current as determined by satellite. Limnol. Oceanogr. 31:927–950.

Reid, F. M. H., C. B. Lange, and M. M. White. 1985. Microplankton species assemblages at the Scripps Pier from March to November 1983 during the 1982–1983 El Niño event. Bot. Mar. 28:443–452.

Reid, J. L. 1987. Physical oceanography, 1947–1987. Calif. Coop. Oceanic Fish. Invest. Rep. 29:42–65.

Reid, J. L., G. I. Roden, and J. G. Wyllie. 1958. Studies of the California Current system, Calif. Coop. Oceanic Fish. Invest. Rep. 6:27–56.

SIO: Scripps Institution of Oceanography. 1984a. Physical, chemical and biological data report, SIO Ref. 84-18, Univ. Calif.

———. 1984b. Physical, chemical and biological data report, SIO Ref. 84-25, Univ. Calif.

Smetacek, V., and U. Passow. 1990. Spring bloom initiation and Sverdrup's critical depth model. Limnol. Oceanogr. 35:228–234.

Smith, P. E. 1971. Distributional atlas of zooplankton volume in the California Current region, 1951 through 1966. Calif. Coop. Oceanic Fish. Invest. Atlas 13.

Smith, R. C., and K. Baker. 1982. Oceanic chlorophyll concentration as determined using Coastal Zone Color Scanner imagery. Mar. Biol. 66:259–267.

Strub, P. T., C. James, A. C. Thomas, and M. R. Abbott. 1990. Seasonal and non-seasonal variability of satellite-derived surface pigment concentrations in the California Current. J. Geophys. Res. 95:11,501–11,530.

Sverdrup, H. V. 1953. On conditions for the vernal blooming of phytoplankton. J. Cous. Cons. Int. Explor. Mer 18:287–295.

Thomas, A. C., and P. T. Strub. 1990. Seasonal and interannual variability of pigment concentrations across a California Current frontal zone. J. Geophys. Res. 95:13,023–13,042.

Tont, S. A. 1989. Climatic change: response of diatoms and dinoflagellates. Aspects of climate variability in the Pacific and western Americas. Geophys. Monogr. 55:161–163.

Venrick, E. L., and T. L. Hayward. 1984. Determining chlorophyll on the 1984 CalCOFI surveys. Calif. Coop. Oceanic Fish. Invest. Rep. 25:74–79.

Venrick, E. L., J. A. McGowan, and A. W. Mantyla. 1973. Deep maxima of photosynthetic chlorophyll in the Pacific Ocean. Fish. Bull. 71:41–52.