CALIFORNIA CURRENT CHLOROPHYLL MEASUREMENTS FROM SATELLITE DATA

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ABSTRACT

A new procedure for rapid quantitative measurement of chlorophyll-like pigment concentrations from data collected by the Coastal Zone Color Scanner on board the Nimbus-7 spacecraft has been implemented. Removal of atmospheric effects revealed ocean features not apparent in the original imagery. Comparison of chlorophyll estimates derived from independent shipboard and satellite data collected concurrently yielded a correlation coefficient of $r = 0.92$.

Satellite chlorophyll images (1260 km on a side) showed a high degree of heterogeneity in the chlorophyll distribution patterns, at all scales. New, recurrent chlorophyll features in the California Current were detected. Comparison of two images collected one month apart showed important changes, both inshore and offshore. Extensive, long-term programs like the California Cooperative Oceanic Fisheries Investigations may largely benefit from the synopticity and repetitive coverage of meaningful satellite observations.

RESUMEN

Ha sido implementado un nuevo procedimiento para la rápida medición cuantitativa de concentraciones de pigmentos clorofílicos utilizando datos obtenidos por el Coastal Zone Color Scanner (Escudriñador en Color de la Zona Costera) a bordo del satélite Nimbus-7. La eliminación de los efectos atmosféricos reveló estructuras oceánicas que no eran visibles en las imágenes originales. La comparación de concentraciones clorofílicas derivadas de los datos adquiridos independientemente, y de manera casi simultánea, por el barco y por el satélite resultó en un coeficiente de correlación de $r = 0.92$.

Las imágenes clorofílicas obtenidas utilizando el satélite (1260 km de lado) mostraron un alto grado de heterogeneidad en los patrones de distribución clorofílica, en todas las escalas. Fueron detectadas estructuras clorofílicas nuevas, de carácter repetitivo, en la Corriente de California. La comparación de dos imágenes obtenidas con un mes de diferencia mostró cambios importantes tanto en la zona costera como en mar abierto. Programas extensivos y a largo plazo, como el California Cooperative Oceanic Fisheries Investigations (CalCOFI), pueden obtener grandes beneficios del carácter sinóptico y repetitivo de observaciones realistas obtenidas desde satélites.

INTRODUCTION

Chlorophyll is an index of phytoplankton abundance (Raymont 1980). Phytoplankton is a major food source in the ocean, at the base of most marine food webs (Ryther 1969). Despite its ecological importance, chlorophyll has been measured in only a few of the California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruises since 1949. Here we show the results of a satellite-related procedure that can repeatedly provide rapid, quantitative measurement of chlorophyll-like pigments over large areas of the ocean. This new approach should allow biological oceanographers to obtain the quantitative chlorophyll field shortly after the fact. It should also permit more efficient interdisciplinary research with other more automated branches of oceanography.

In its 1981 report, the CalCOFI Committee (Reid et al. 1981) discussed the desirability of reducing ship time and the areal scope of ship operations, while trying to preserve the integrity of the CalCOFI time series (at least at the level of resolution of low-frequency, large-scale events). Recently, complementary shipboard and satellite data (Bernstein et al. 1977; Lasker et al. 1981; Smith et al. submitted), and complementary coastal and satellite data (Peláez 1981) have successfully studied oceanographic problems in the California Current region. Results presented here strongly suggest that extensive, long-term programs like CalCOFI may benefit from the synopticity and repetitive coverage of meaningful satellite observations.

In this report we outline a procedure for rapidly obtaining remotely sensed estimates of chlorophyll concentrations. We compare the derived data to shipboard measurements, estimate the accuracy of the method, and show some typical chlorophyll patterns in the California Current.

DATA AND METHODS

Shipboard Data

Shipboard data collected during the May-June 1981 CalCOFI cruises of R/V *David Starr Jordan* and R/V *New Horizon* included a wide variety of oceanographic measurements (temperature, salinity, oxygen,

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phosphate, nitrate, nitrite, silicate, chlorophyll-a, primary production, and zooplankton) in the water column of the California Current, at fixed CalCOFI stations from about 28°N to about 38°N. Along ship tracks temperature and salinity were measured with a thermosalinograph. R/V *David Starr Jordan* covered from about 28°N to about 33°N, and also performed continuous underway fluorometric determinations of chlorophyll using a Turner Designs model 10 continuous-flow-through fluorometer. Discrete determinations of the chlorophyll to fluorescence, and of chlorophyll-a to phaeopigments-a ratios (Lorenzen 1966; Strickland and Parsons 1972) were done frequently (about every two hours) with a Turner model 111 fluorometer.

Procedure for Deriving Quantitative Chlorophyll-Like Pigment Estimates from the Satellite Data

The Coastal Zone Color Scanner (CZCS) was designed to measure phytoplankton pigment concentrations in the ocean (Hovis et al. 1980) using narrow (20 nm) spectral bands centered at 443, 520, 550, and 670 nm (the instrument also has two wider bands centered at 750 and 11,500 nm). Satellite determinations of chlorophyll are possible because the upwelled spectral radiance just beneath the sea surface contains valuable information about the constituents of the water. Phytoplankton, which contains the photosynthetically active pigment chlorophyll-a, plays a dominant role in the processes of absorption and scattering of visible light within the water (especially at specific wavelengths), except for unusual ocean regions like land-related discharge areas. At 443 nm, chlorophyll-a absorption is strong, and the solar radiation backscattered out of the ocean decreases rapidly with increasing chlorophyll-a concentrations. At 520 and 550 nm, near the so-called "hinge point" (Duntley et al. 1974), upwelled radiance variations are less dependent on chlorophyll concentrations. Bands available in the CZCS cannot separate chlorophyll-a from phaeopigments-a, a degradation product of chlorophyll-a, because both have almost the same absorption spectrum: hence the term *chlorophyll-like pigments* for the estimations obtained with this sensor. Accessory pigments (chlorophyll-c and carotenoids) may also contribute to total absorption in the 443 nm band. Statistical relationships between chlorophyll-like pigment concentrations (hereafter called simply chlorophyll concentrations), and ratios of upwelled subsurface spectral radiances at various wavelengths have been obtained (Clarke et al. 1970; Arvesen et al. 1973; Hovis and Leung 1977; Morel and Prieur 1977; Gordon and Clark 1980a; Gordon et al. 1980).

The atmosphere between the sea surface and the spacecraft poses an important problem for the quantitative remote sensing of chlorophyll concentrations in the ocean. Atmospheric scattering contributes about 80% of the radiance detected by the satellite sensor, at about 950-km altitude. The main problem in obtaining the desired subsurface signal is the removal of the aerosol scattering component. Aerosols vary considerably in concentration, composition, and size distribution over space and time. We have developed a relatively simple and practical procedure to remove the atmospheric influence on the CZCS imagery without the requirement of shipboard optical measurements (Guan, in preparation). Processing was done on subscenes of about 420 km on a side, and larger coverages were treated subscene by subscene. The spectral information contained in a subscene was split into two components: a fluctuation and a constant background. The fluctuating component included the aerosol and subsurface radiant contributions, and a small variation of the Rayleigh scattering background.[1] This regular variation of the Rayleigh scattering with increasing scan angle was removed by subtracting a sloping gray wedge obtained from the difference in Rayleigh scattering radiance at both sides of each subscene.

The aerosol and the subsurface radiant contributions had different spectral signatures. Aerosol scattering was assumed to change linearly with optical thickness (Gordon and Clark 1980a). Aerosol radiant fluctuations δLa at two wavelengths λ_2 and λ_1 were considered proportional to each other

$$\delta La(\lambda_2) = \Delta(\lambda_2,\lambda_1)\delta La(\lambda_1),$$

where $\Delta(\lambda_2,\lambda_1)$ is the proportionality constant. $\Delta(\lambda_2,\lambda_1)$ was determined by regression analysis of two CZCS spectral images over areas with evident changes in aerosol content. As a first approximation, a linear relationship between the fluctuations of upwelled subsurface radiances at different wavelengths was used. A nonlinear relationship was also considered. Differences in the corrected result between the nonlinear and linear cases were usually small, except under extreme conditions. Therefore, the linear relationship was preferred for this study. Aerosol fluctuations were separated from subsurface fluctuations using this two-dimensional linear model, in an image-element-by-image-element basis. Removal of the atmospheric variations clearly revealed the ocean patterns, although each spectral image still had a constant background corresponding to a clear and even atmosphere. The constant backgrounds were removed

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[1] Larger scan angles and changes in the wind field result in changes in the reflection characteristics of the sea surface. Their effects on the CZCS imagery appeared to be very similar to the aerosol fluctuations, and were mostly eliminated after removal of aerosol scattering from the images.

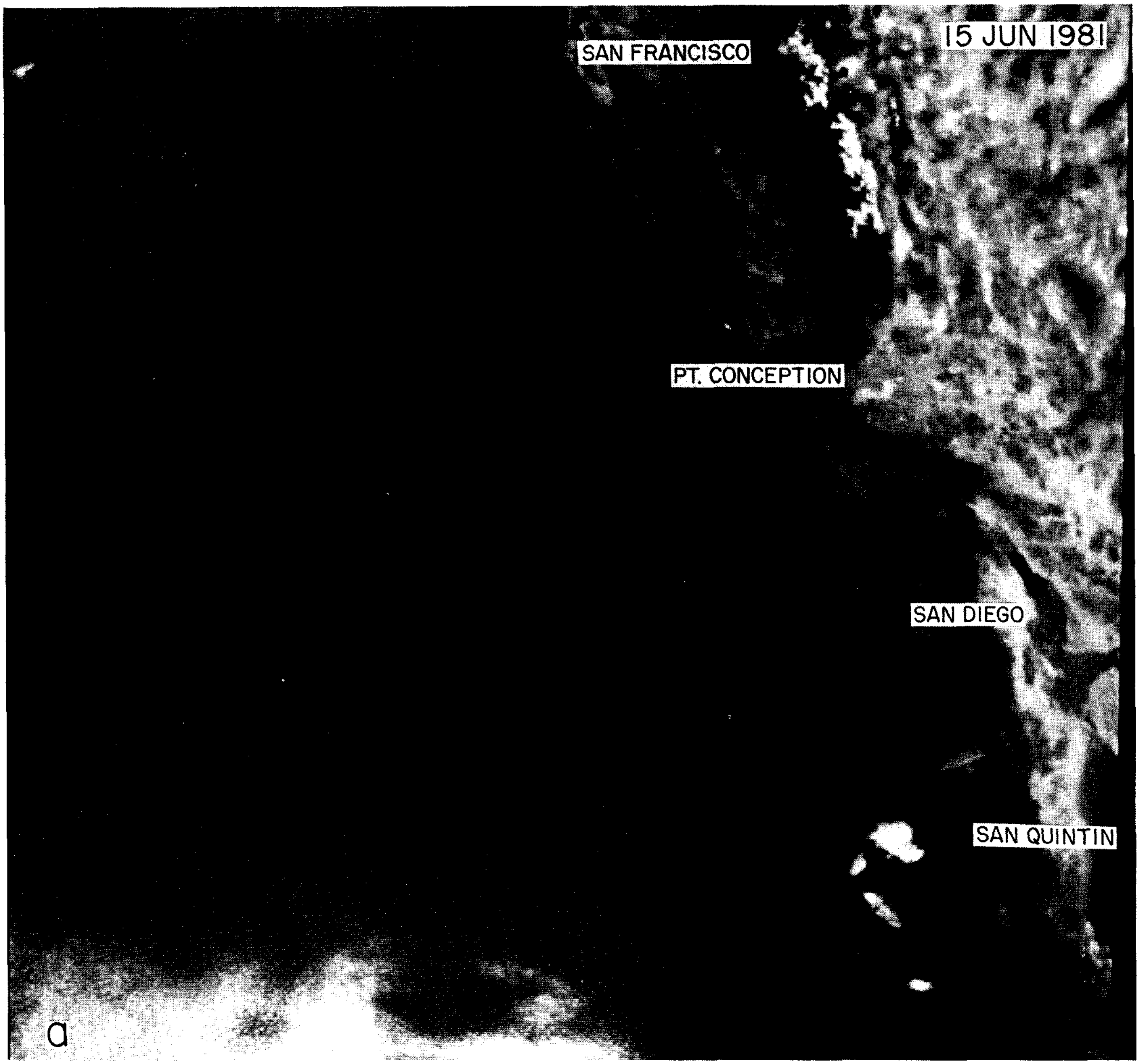

Figure 1a. Comparison of Nimbus-7 CZCS band 1 (443 nm) radiances off the Californias before atmospheric correction. Data-collection time was approximately four minutes near local noon on June 15, 1981. The image is about 1260 km on a side.

by setting appropriate bias values. Bias settings were selected considering the high stability of the spectral reflectance of clear seawater.[2] Sequential analyses of images at the same location under changing atmospheric conditions have shown that the atmospheric correction yields consistent results. Chlorophyll concentrations were estimated from ratios of the corrected upwelled subsurface spectral radiances at various wavelengths (Gordon and Clark 1980a). Using ratios may eliminate the effect of undesired covarying influences in the divided bands. The processed CZCS data are entirely independent of the May-June 1981 CalCOFI shipboard data, which were used only to test the procedure.

Satellite Data

Satellite data from the CZCS on board the Nimbus-7 spacecraft were collected and totally processed at the Remote Sensing Facility of the Scripps Institution of Oceanography. CZCS data ground resolution at nadir is about 0.8 km. Data-collection time by the spacecraft for any of the images presented here

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[2] Locating clear water areas in the imagery has not been a limitation while processing data off California, but in some cases it might require comparison with neighboring subscenes.

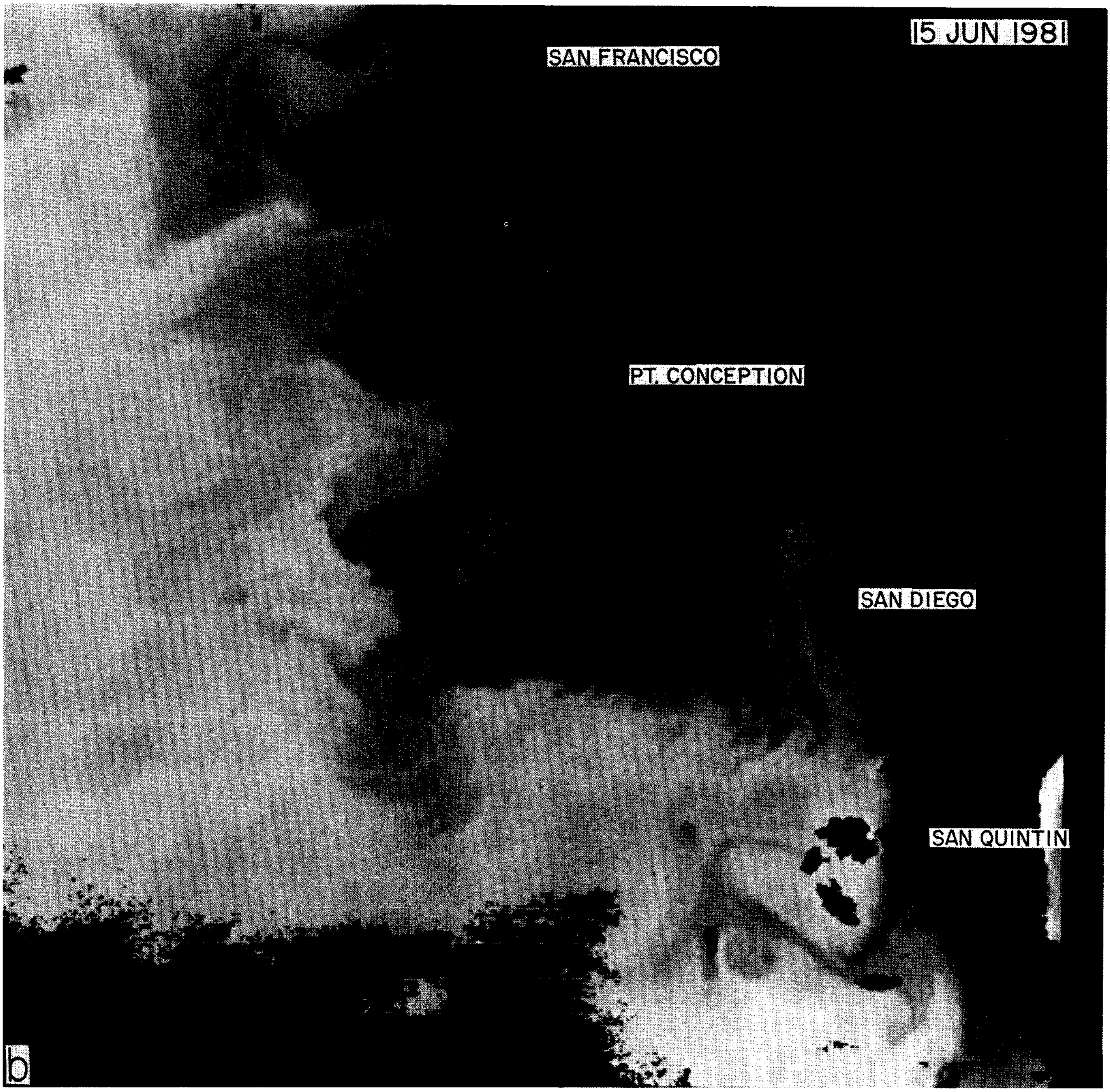

Figure 1b. Same data as in Figure 1a, but after atmospheric correction. The procedure cleaned up haze and revealed ocean features not apparent in the uncorrected image. Land and clouds have been masked in black.

is less than four minutes, at about local noon. A black mask over land and clouds has been applied to all the corrected images (but not to the uncorrected images in Figures 1a and 2a). Lighter gray tones correspond to higher chlorophyll concentrations (except for the absorption images in Figure 1). Some anomalous lighter or darker areas in the vicinity of clouds should be considered cautiously or disregarded since they may be due to cloud structures smaller than an image element (about 0.68 km^2), for which the atmospheric correction may not account.

RESULTS AND DISCUSSION

The Atmospheric Correction

The atmospheric correction procedure was applied to an almost cloud-free image off the Californias from San Francisco to Vizcaíno Bay (about 38°N to about 28°N), on June 15, 1981 (Figures 1 and 2). Images are

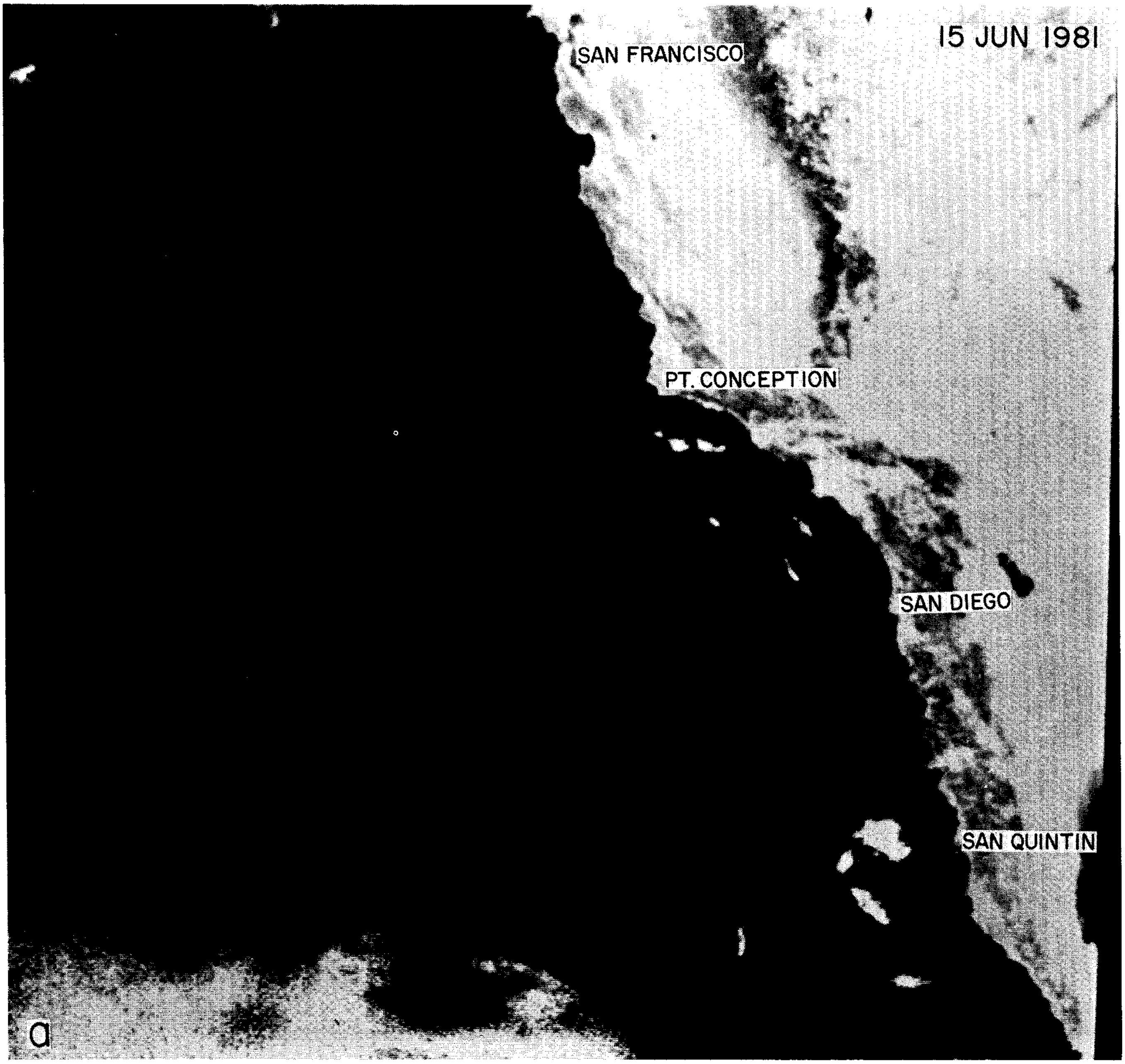

Figure 2a. Nimbus-7 CZCS band 3 (550 nm) radiances before application of the atmospheric correction procedure. Other characteristics are the same as in Figure 1a.

about 1260 km on a side. Images in Figure 1 show CZCS band 1 data (443 nm) before and after application of the correction procedure. Darker gray tones represent stronger absorption areas. The atmospheric correction cleaned up haze and aerosols to reveal ocean features not apparent in the uncorrected image. Figure 2 is the analog of Figure 1, for the CZCS band 3 data (550 nm). Lighter gray tones represent stronger backscattering areas. The corrected image (Figure 2b) shows again a large amount of detail and mesoscale structures that were covered by the overlying atmosphere (Figure 2a). The atmospheric contribution relative to the subsurface contribution is stronger at 550 nm (Figure 2a) than at 443 nm (Figure 1a). This, combined with the coarser onboard digitization scheme for the lower-frequency bands of the CZCS, resulted in less smooth transition from darker to lighter gray tones in the 550-nm corrected image (Figure 2b). More even images can be obtained by applying data-smoothing techniques while applying the atmospheric correction. However, to preserve as much detail as possible, we applied no smoothing.

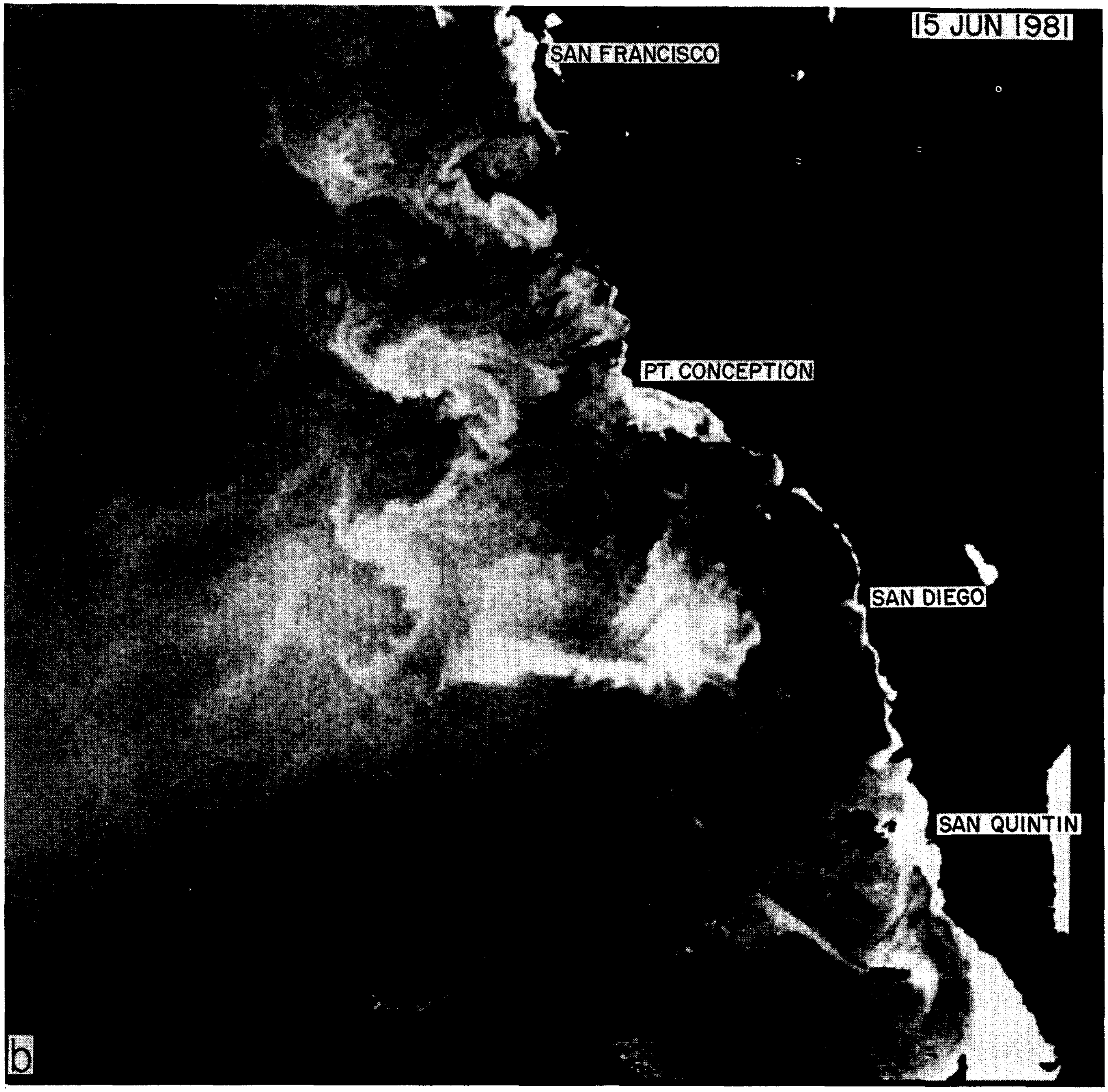

Figure 2b. Same data as in Figure 2a, but after application of the atmospheric correction. The procedure disclosed mesoscale structure and finer details that were concealed by the overlying atmosphere in the uncorrected image.

Comparison of Satellite and Shipboard Chlorophyll Measurements

On June 13, 1981, R/V *David Starr Jordan* steamed from near Guadalupe Island, in Central Baja California, back to San Diego, yielding a fairly long (about 450 km) continuous shipboard transect of underway, calibrated chlorophyll measurements (light track line in Figure 3). A relatively cloud-free CZCS image was collected concurrently. These two data sets allowed us to perform quantitative comparisons between the satellite and the shipboard measurements. The only criterion used to select the June 13 data sets was the availability of concurrent shipboard and satellite measurements over the same cloud-free area. The complete chlorophyll procedure was applied to the June 13, 1981, CZCS data off southern California and northern Baja California (Figure 3) from about 33°N (Del Mar) to about 29°N (northern edge of Guadalupe

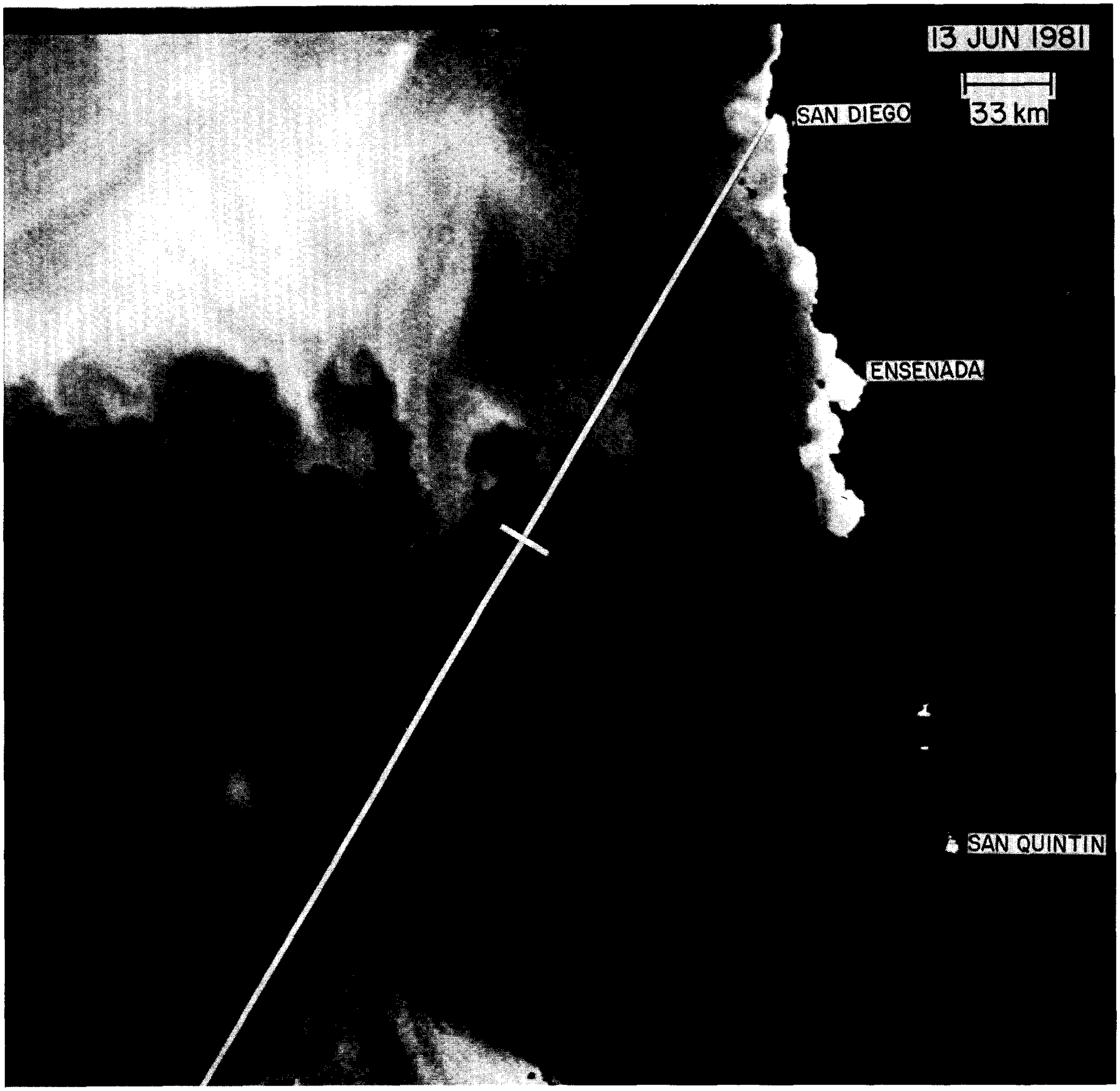

Figure 3. Processed chlorophyll-like pigment image off southern California and Baja California derived from the Nimbus-7 CZCS imagery (ligher gray tones correspond to higher chlorophyll concentrations). The light track line was followed by R/V *David Starr Jordan* on her way back to San Diego, from about 9 p.m. June 12, 1981, to about 7 p.m. June 13, 1981, local times (black area near the end of track line corresponds to a cloud). Data-collection time was less than two minutes, near local noon on June 13, 1981. Image is about 420 km on a side.

Island, in bottom left of Figure 3). The southern part of the ship track showed a flat, monotonous chlorophyll profile, and the same feature was apparent in the satellite profile. Since our main concern was comparing how well the satellite measurements were able to detect changes in the chlorophyll field in relation to the shipboard measurements, we discarded most of the flat part of the profiles. The light track line between the tick mark and San Diego in Figure 3 shows the approximately 190-km ship track used for the quantitative comparison between shipboard and satellite chlorophyll concentrations. Individual image elements of the satellite chlorophyll data were sampled at maximum resolution. Every other image element was compared to the corresponding value of the shipboard transect. Therefore, no smoothing or averaging was applied to the data.

Superimposed ship and satellite transects (Figure 4)

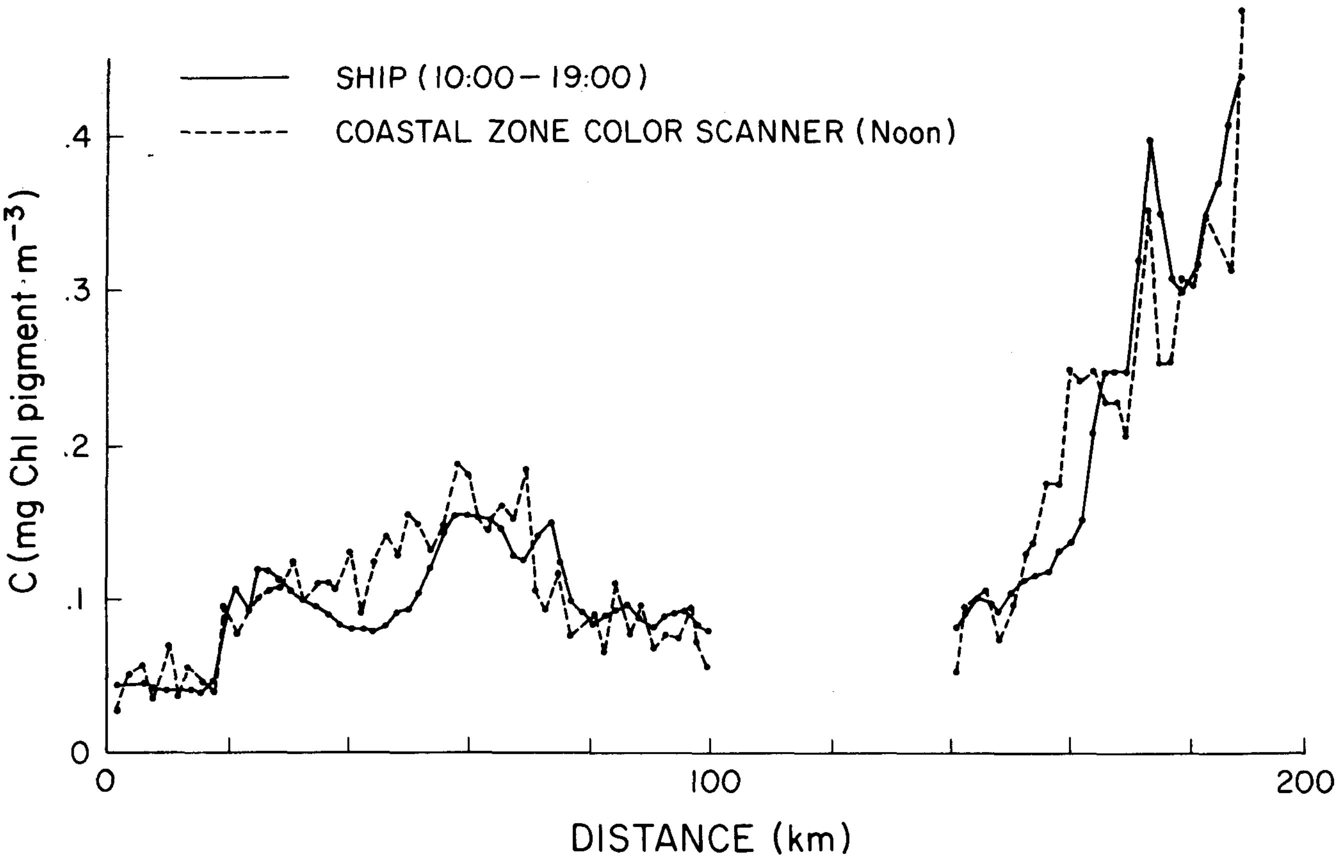

Figure 4. Comparison of independent shipboard and satellite chlorophyll-like pigment concentrations collected concurrently along the northern segment of track line shown in Figure 3, by R/V *David Starr Jordan* and by the Nimbus-7 CZCS (distance coordinate runs from tick mark to San Diego). Satellite data were sampled at full resolution (1 km) on every other image element. There is good agreement between the satellite and the shipboard measurements.

show that shape of satellite and shipboard horizontal chlorophyll profiles is quite similar, although some disparity exists at about 50 km from the origin of the transect. Chlorophyll features seem to be detected similarly by satellite and shipboard sensors, but satellite measurements appear to have larger high-frequency variability, especially in the areas of lower chlorophyll values. Relative displacement between the two profiles (right portion of Figure 4) added low-frequency variability to the comparison near the coast as the satellite overpass and the shipboard sampling became separated in time. The satellite sensor seems to be detecting low chlorophyll concentrations quite well, and there appears to be good agreement between the satellite and the shipboard measurements (notice that coordinates in both Figures 4 and 5 are linear).

The quantitative comparison of satellite and shipboard chlorophyll concentrations collected concurrently yielded a correlation coefficient of 0.92 (Figure 5). This accounts for about 85% of the variance (coefficient of determination $r^2 = 0.85$), and it seems unlikely that satellite and shipboard sensors would be measuring different things. We emphasize the point that satellite and shipboard information are two independent data sets. That is, no shipboard information is needed to process the CZCS imagery in order to obtain the quantitative chlorophyll field.

To get an idea of the temporal rate of change of chlorophyll in the ocean, the same shipboard transect was compared with a satellite transect obtained two days later and in the same location. The correlation coefficient dropped by 0.23, from 0.92 in the quasi-simultaneous case to 0.69 ($r^2 = 0.47$) in the two-day-lag case. Inspection of the later chlorophyll image showed that higher-chlorophyll water from the northwest was drifting across the ship track. This shows that advective transport may significantly change the chlorophyll concentrations in a short period of time. Another example is illustrated by the horizontal bar in Figure 5. This shows the temporal variability of surface chlorophyll as measured from the ship while it remained at a fixed location for two days. The range of values here is about the same as the point scatter in the regression.

Nonsimultaneity of shipboard and satellite measurements apparently added an important low-frequency variability component to the ship-satellite comparison. Noise in the satellite signal, and limitations imposed by the digitization scheme on board the spacecraft further introduced high-frquency variability. Variability was also introduced by possible navigation errors, and by the chlorophyll measurement process in the shipboard technique. All these added variabilities do not result from actual disaccord between the shipboard and satellite approaches, but do contribute to point scatter in the ship-satellite chlorophyll diagram. High-frequency variability in the satellite data could have been reduced by applying data-smoothing techniques, or by averaging contiguous image elements instead of sampling each element individually at full resolution. We did not do this because of concern with the results of the procedure in an image-element-by-image-element basis. Further simultaneous comparison of shipboard and satellite transects at higher chlorophyll concentrations than those shown in Figure 4 was obstructed by cloud cover. However, examination of the extensive 26-day shipboard continuous underway chlorophyll data set showed that the nonsimultaneous shipboard and satellite estimates of chlorophyll were also in good agreement in the areas of highest chlorophyll concentration (2-3 mg m^{-3}) encountered by R/V *David Starr Jordan*.

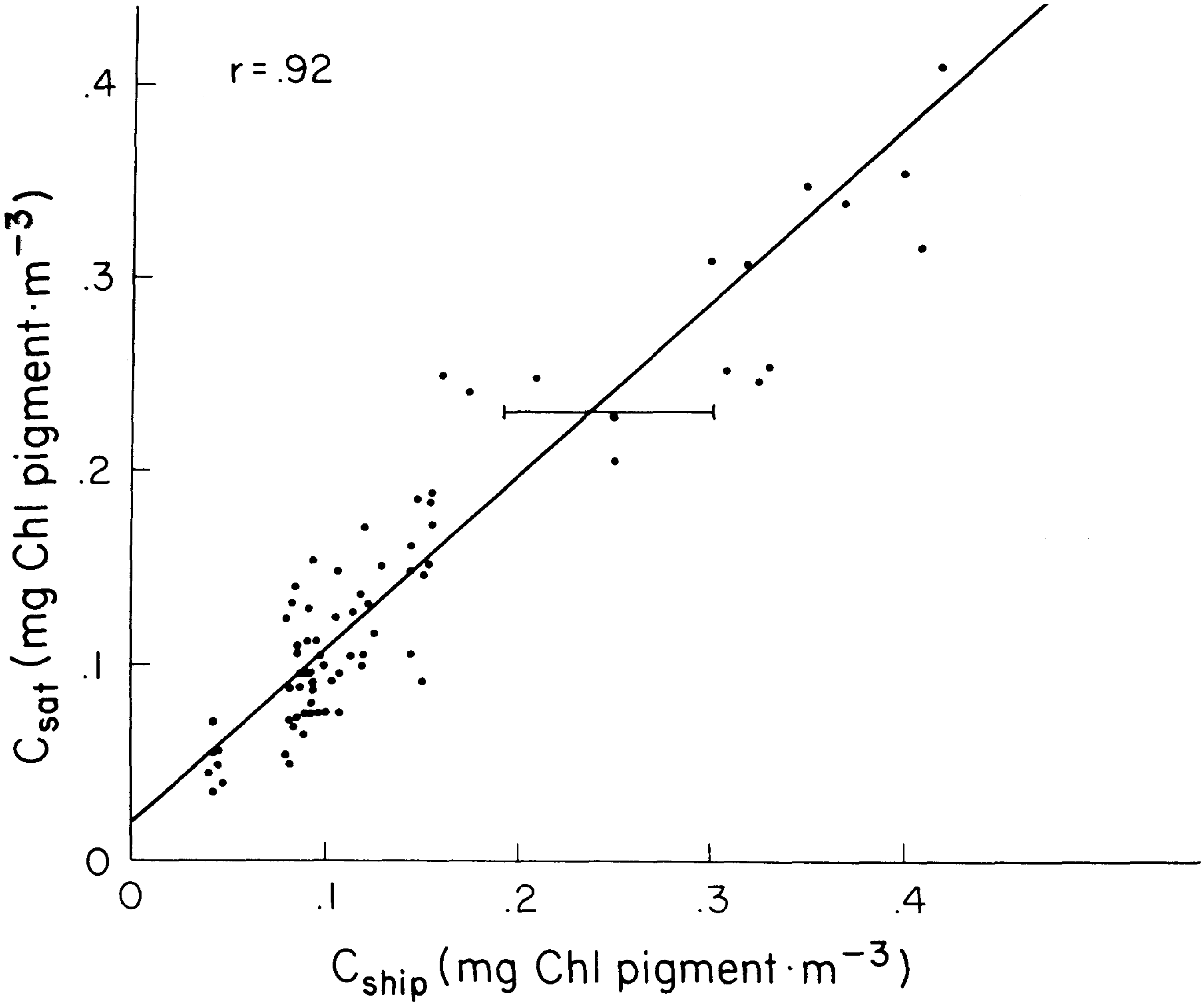

Figure 5. Quantitative comparison of independent shipboard and satellite chlorophyll-like pigment measurements (from Figure 4), collected almost concurrently, yielded a significant correlation coefficient (r = 0.92). Horizontal bar is a typical example of shipboard chlorophyll variability at a fixed location over a two-day period. Notice that the range of values here is about the same as the point scatter in the regression.

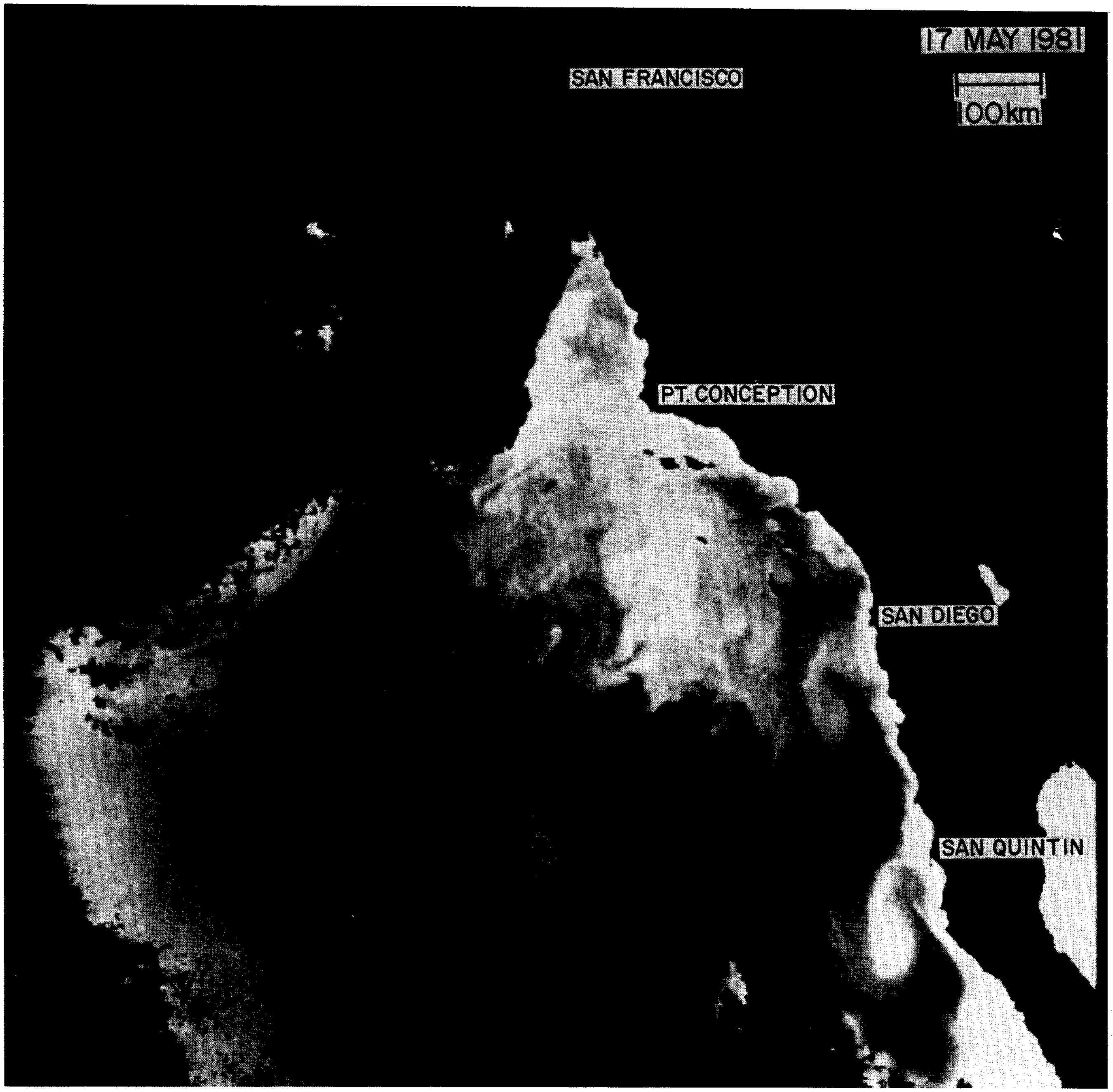

Figure 6. Processed chlorophyll-like pigment image off the Californias, near noon May 17, 1981, derived from the Nimbus-7 CZCS imagery. Lighter gray tones correspond to higher chlorophyll concentrations except in the vicinity of clouds, where they may be due to subimage-element-size cloud structures (these structures can escape cloud masking, and are not corrected by the atmospheric correction procedure). Notice "shelf-attached" eddies at San Quintín and south of San Diego, the higher-chlorophyll region farther offshore, and the large degree of heterogeneity in the chlorophyll distribution patterns at all scales (image is about 1260 km on a side).

Satellite Chlorophyll Distribution Patterns and Their Temporal Changes

The complete procedure to obtain chlorophyll concentrations was applied to the May 17, 1981, CZCS data off the Californias, from San Francisco to Vizcaíno Bay (about 38°N to about 28°N). A high degree of chlorophyll heterogeneity is evident in this 1260-km-on-a-side image (Figure 6). Intense high-chlorophyll areas (lighter gray tones) occur off Pt. Buchon, Pt. Conception, and in the Santa Barbara Channel. The largest high-chlorophyll (1-2 $\mathrm{mg\,m^{-3}}$) region occurs in the middle of the image, overlying the system of shallow submarine ridges and banks (shallower than 500 m, often less than 200 m) that extends from Santa Rosa Island to 200-300 km to the southeast. Complementary chlorophyll and thermal infrared satellite imagery analyses have shown that cooler water and higher-chlorophyll waters persist year round in this area, even if the areal extension and intensity of the signals do change with season (Peláez, in preparation). Geographic location of this "hot spot" corresponds to location of the Southern California Eddy (Sverdrup and Fleming 1941; Reid et al. 1958; Schwartzlose 1963; Owen 1980). According to chlorophyll and thermal infrared satellite observations, the Southern California Eddy appears to be associated with the shallow bottom topography of this region, and seems to be partly the result of water impinging against the system of shallow ridges and banks in this area.

The transition zone from the high-chlorophyll area in the middle of the image to the lower-chlorophyll regions surrounding it is characterized by tongues and eddies, usually bent clockwise. A narrow (a few km wide), high-chlorophyll (usually higher than 1 mg m^{-3}) band is present all along the coastline. Immediately offshore, a lower-chlorophyll (.2-.5 mg m^{-3}) region, about 100 km wide, overlies the deep troughs and basins that characterize most of inshore southern California. Two fairly large (about 100 by 50 km), high-chlorophyll (1-1.5 mg m^{-3}), counterclockwise eddies protrude into the lower-chlorophyll, nearshore region. These eddies have long stems or filaments "attaching" them to the Coronados (south of San Diego) and San Quintín (in Baja California) shelves. Both have been detected with satellite imagery on other occasions; they are recurrent features of the California coastal region. Both appear to be related to coastal upwelling centers detected with satellite thermal infrared imagery over the Coronados and the Colnett-San Quintín shelves (Peláez, in preparation). Also, a smaller, counterclockwise "attached" eddy is present in the Newport-Dana Pt. area. Two smaller free eddies occur off Pt. Conception and off Pt. Buchon.

By June 15, an overall decrease in the chlorophyll concentrations was apparent (Figure 7). Also, important changes in the chlorophyll distribution patterns had occurred, both inshore and offshore. An unexpected, latitudinally oriented sharp boundary, starting about 100 km off Ensenada and extending 400-500 km offshore, was detected. Also, enhanced eddy activity associated with a conspicuous meridional, frontal strengthening far offshore (200-500 km off the coast and about 400-500 km long) was concurrent with generalized offshore displacement (or extension) of the major high-chlorophyll structures. By mid-June, the "attached" eddies had disappeared. The low-chlorophyll inshore southern California waters became more continuous with lower-chlorophyll waters to the south. Some new features became apparent. Four large (about 200 km in diameter) clockwise vortices, or gyres, were lined up meridionally far away from the coastline. They appeared to be the low-chlorophyll (about .1 mg m^{-3}), offshore component of the meridional frontal zone mentioned above. New high-chlorophyll structures could also be seen by mid-June: a small counterclockwise eddy developing off Pt. Reyes, two adjacent eddies off Monterey, two joint eddies in the Santa Barbara Channel, a high-chlorophyll V-shaped structure associated with Cortes Bank, and a small chlorophyll patch (north of Guadalupe Island) in the middle of a large low-chlorophyll region. Thus in approximately one month there were significant large-scale and mesoscale changes in the chlorophyll patterns.

Meaning of Satellite Chlorophyll Measurements

The question often arises: How representative are the satellite chlorophyll measurements in terms of the chlorophyll content of the entire water column? The maximum depth penetration of the remotely sensed signal (Gordon and McCluney 1975; Gordon and Clark 1980b; Smith 1981) varies depending on the amount and vertical distribution of suspended matter in the water column. In areas not strongly influenced by terrigenous material, this depth is primarily determined by the light absorption of biological material, and is far less affected by scattering. Therefore, when chlorophyll concentrations are low in the surface layers, the remotely sensed signal will reach larger depths than when a surface layer of high chlorophyll is present (complications arise because this effect is dependent on the wavelength of light).

Hayward and Venrick (submitted), using data of the May-June 1981 CalCOFI cruises, found that surface chlorophyll had a highly significant correlation with integrated chlorophyll ($r = 0.86$, $p < 0.01$), and with integrated primary production ($r = 0.87$, $p < 0.01$) in the euphotic zone (from the surface to the one-percent light level) of the California Current. Smith and Baker (1978) used the average chlorophyll concentration from the surface to one attenuation depth (defined as the inverse of the total diffuse attenuation coefficient for irradiance) as an approximation of the remotely sensed chlorophyll. They found that it was significantly correlated with average chlorophyll ($r = 0.95$, $p < 0.01$) and with average primary production ($r = 0.85$, $p < 0.01$) in the water column, from the surface to the one-percent light level. They used a large shipboard data set, collected over a wide range of geographical regions. Hayward and Venrick's May-June 1981 CalCOFI data set allowed us to consider the weighted integral of the shipboard verti-

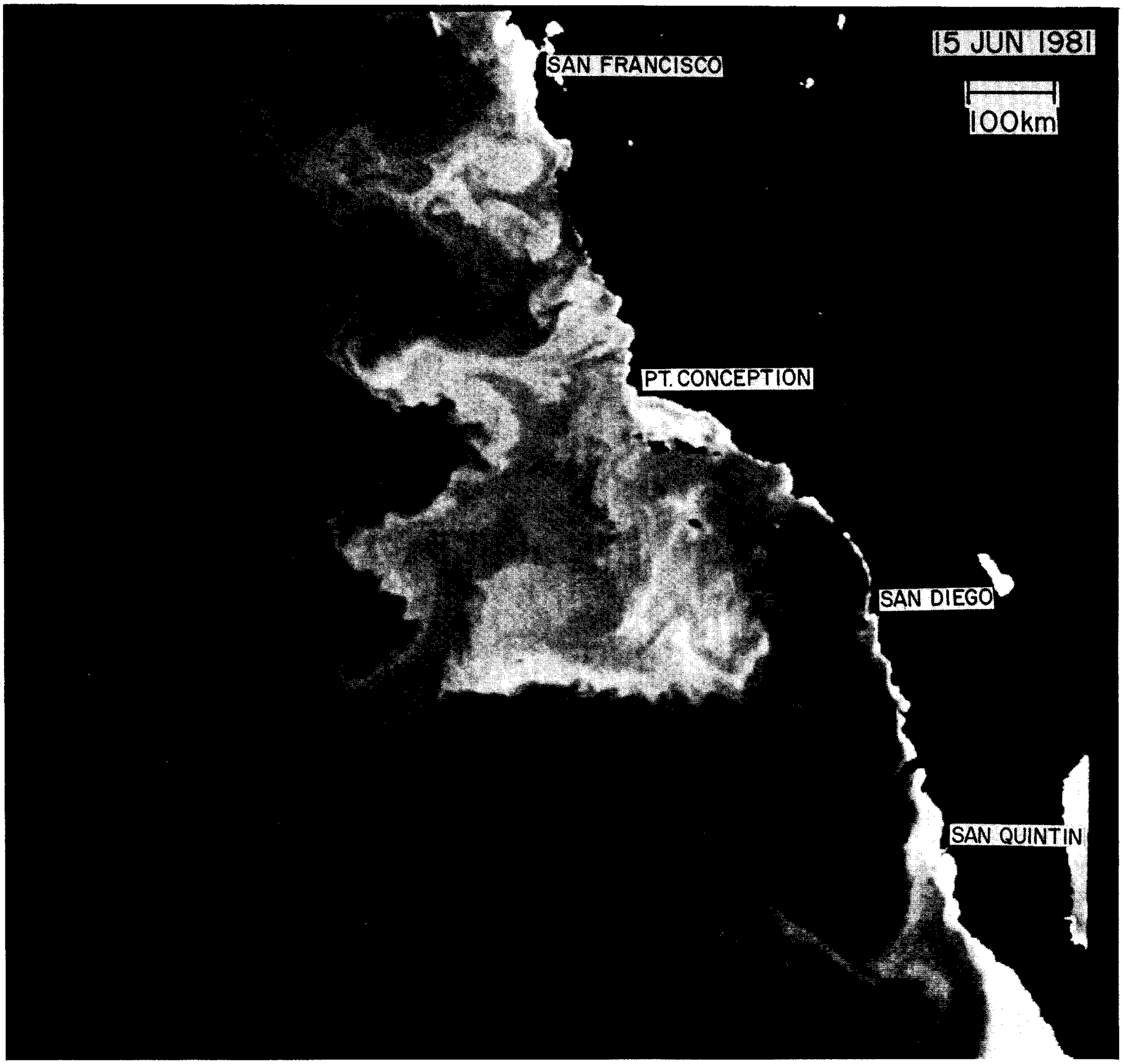

Figure 7. Similar to Figure 6 on June 15, 1981. Besides an overall decrease in the chlorophyll-like pigment concentrations, important changes have occurred in the chlorophyll distribution patterns, both inshore and offshore, during the intervening month. Note the unexpected, latitudinally oriented, sharp boundary offshore, south of San Diego.

cal profiles as an approximation of satellite chlorophyll. The weighting function represents the depth penetration of the remotely sensed signal under variable vertical distributions of chlorophyll. The weighted integral only slightly improved Hayward and Venrick's results ($r = 0.87$ for integrated chlorophyll, and $r = 0.90$ for integrated primary production). One should be careful in interpreting these high correlation coefficients (Smith 1981; Smith et al., submitted; Hayward and Venrick, submitted), especially for areas with significant changes in the vertical distribution of chlorophyll at larger depths than the maximum penetration depth of the remotely sensed signal. On the other hand, the high correlation coefficients suggest that, within regions like the California Current, the remotely sensed, upper-layer chlorophyll may indicate more general ecological conditions prevailing in the area.

Uses of Satellite Observations

Results presented here show that satellite measurements can help solve oceanographic problems. The wide range of spatial and temporal scales available in satellite observations can help resolve some questions difficult to answer with ships only. Ground resolution (800 m) and temporal coverage (daily, clouds permitting) of satellite determinations of chlorophyll with the CZCS appear adequate in terms of the spatial and temporal scales of phytoplankton populations (km's to 100's of km's; days to weeks). Upper-layer chlorophyll heterogeneity over large areas of the ocean, as well as rate of change of chlorophyll distribution patterns, may be assessed. However, one must be aware that satellite observations yield upper-layer chlorophyll concentrations; i.e., an index of only one component of the system, with some limitations. Therefore, satellite measurements should be coupled with detailed shipboard measurements if one expects to understand oceanographic phenomena and processes.

Extensive, long-term programs like CalCOFI may largely benefit from the synopticity and repetitive coverage of satellite observations. A balanced ship-satellite complementary approach to oceanographic questions can allow more efficient use of ships. Satellites rapidly survey large areas of ocean and can help in designing sound and flexible sampling schemes, allowing for real time ship-satellite collaboration, if necessary. Satellite observations are able to detect "hot spots," stable or variable regions, and northern, southern, or offshore influences. Also, they can rapidly spot frontal areas or other zones of specific interest. This information is important for appropriately defining "indicator stations," geographically and through time, in a heterogeneous and dynamic region like the California Current. Satellite imagery can also help assess the degree to which indicator stations are representative of larger areas of ocean. Furthermore, one can keep the spatial and temporal high-frequency part of the variability, which may be relevant to some oceanographic questions. The enhanced spatial and temporal resolution of observations may also provide insight into processes and dynamic characteristics of the California Current.

SUMMARY

1. A new procedure for quantitative measurement of chlorophyll concentrations from data collected by the Coastal Zone Color Scanner on board the Nimbus-7 spacecraft has been implemented.
2. Removal of atmospheric effects from the satellite data revealed ocean features not apparent in the original imagery.
3. Comparison of independent shipboard and satellite chlorophyll concentrations collected concurrently yielded a correlation coefficient of $r = 0.92$. Similar comparison with satellite data collected two days later (while higher-chlorophyll water was being advected across the ship track) showed a 0.23 decrease ($r = 0.69$) in the correlation coefficient.
4. Chlorophyll satellite images (1260 km on a side) showed a high degree of heterogeneity in the chlorophyll distribution patterns, at all scales. Comparison of two images collected one month apart showed important changes, both inshore and offshore.
5. A weighted integral of the shipboard chlorophyll vertical profiles (weighted by the depth penetration of the remotely sensed signal) was highly correlated with integrated chlorophyll ($r = 0.87$, $p < 0.01$) and with integrated primary production ($r = 0.90$, $p < 0.01$) in the euphotic zone (one-percent light level) of the California Current. This suggests that within this region the remotely sensed, upper-layer chlorophyll may indicate more general ecological conditions prevailing in the area.
6. Quantitative satellite determinations of chlorophyll should allow biological oceanographers to obtain the quasi-instantaneous chlorophyll field shortly after the fact. This should permit more efficient interdisciplinary research (by contributing to bridge the data-processing-time gap) with other more automated branches of oceanography.
7. The satellite imagery allowed us to detect new, recurrent, high-chlorophyll features in the California Current: eddy pairs off Monterey and in the Santa Barbara channel; counterclockwise eddies "attached" to the San Quintín, Coronados, and Pt. Reyes shelves; and a large, persistent, high-chlorophyll region overlying the shallow ridges and banks off southern California. A narrow (a few km) high-chlorophyll band was present all along the coastline. A lower-chlorophyll region (about 100 km wide) overlaid the deep troughs and basins of inshore southern California. Two intense frontal regions were also detected: an unexpected, latitudinally oriented, sharp boundary, starting about 100 km off Ensenada and extending 400-500 km offshore; and another, meridionally oriented, meandering far offshore (200-500 km), and about 400-500 km long. Four large, low-chlorophyll gryes, or vortices, were lined up longitudinally in the offshore side of the meridional front.
8. Extensive, long-term programs like CalCOFI may largely benefit from the synopticity and repetitive coverage of meaningful satellite observations. Complementary ship-satellite measurements can

allow more efficient use of ships, may help to appropriately define "indicator stations" (and assess their representativity later on), and can rapidly spot frontal areas or other zones of specific interest.

9. Satellite measurements yield upper-layer chlorophyll concentrations; i.e., an index of only one component of the system, and with some limitations. Therefore, satellite measurements should be coupled with detailed shipboard measurements.
10. The procedure used here to derive quantitative estimates of chlorophyll from satellite observations is being further tested, as concurrent shipboard and satellite data becomes available, to determine whether changes are needed to apply it to other seasons and to other areas.

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