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Variability of the ocean surface color field in central California near-coastal waters as observed in a seasonal analysis of CZCS imagery

by Vittorio Barale and Ruth Wittenberg Fay

ABSTRACT

A time series of Coastal Zone Color Scanner images has been analyzed, on a seasonal basis, to gain a perspective on the ocean surface color field heterogeneity in central California near-coastal waters. Seasonal composite maps of the diffuse attenuation coefficient at 490 nm were derived, in the form of arithmetic means and corresponding variances, for the years 1981, 1982 and 1983. By identifying “open ocean,” “transition” and “coastal” water types in the mean images, and comparing values and areal extension of each class in different periods and years, a distinct seasonality of the spatial characteristics of ocean color emerged. Analogous seasonal cycles are evident in the variance images. Both parameters present a more pronounced, extensive and convoluted surface structure in the spring-summer periods, followed by an intermediate stage in fall and much reduced variability in the winter periods. This seasonal trend is maintained regardless of the high degree of interannual variability most evident in the spring-summer conditions. Possible interpretations of the imagery in terms of the oceanographic “climate” of the region are discussed, as reflecting the combined effects of coastal processes and offshore mesoscale dynamics typical of the California Current System. A profound influence of the bathymetric relief on surface structure, even in deep ocean areas, is finally documented by the data set.

1. Introduction

The ocean surface color field, and its spatial and temporal variability, has received a great deal of attention in recent years. Interest in this topic has been largely motivated by the development of remote sensing techniques, which can complement synoptic surveys to enhance the sparse shipboard data previously available. Since ocean color is affected by the water constituents, these techniques allow for large scale, high resolution assessments of their concentration and heterogeneity through the measurement of surface optical properties.

Together with suspended sediments and “yellow substance” (material derived by the degradation of land and marine organic remains), the photosynthetic pigments (primarily chlorophyll-a) of phytoplankton control the fate of visible light as it penetrates downward from the sea surface. Moreover, away from the very near-coastal
area, phytoplankton and their associated pigments from the first optical depth (defined as the depth at which natural sunlight has decayed to \(1/e\) of its surface value) are the most important contributors to ocean color (Morel and Prieur, 1977; Clark et al., 1980; Smith, 1981). The planktonic ecosystem, in turn, is strongly regulated by physical processes of the oceanic environment (such as horizontal advection, upwelling and vertical mixing) and their interactions with the bathymetric morphology of a basin (Legendre and Demers, 1984, and references therein). Hence the possibility of using optical remote sensing to study the spatial and temporal structure of the biological environment, in relation to ocean dynamics.

The heterogeneity of surface optical properties is particularly complex in an eastern boundary current such as the California Current System, which has long been recognized as one of the most dynamic and biologically active areas in the world's oceans (Hickey, 1979; Walsh, 1977). Satellite observations have provided striking documentation of the mesoscale meanders and eddies superimposed on the large-scale mean flow of the California Current, and of chlorophyll-like pigment concentration levels up to an order of magnitude larger than found elsewhere (Bernstein et al., 1977; Smith and Baker, 1982; Smith et al., 1982; Pelaez, 1984).

In the present work, we have utilized a time series of satellite images to document the heterogeneity of the surface color field in the central California near-coastal region over a period of three years. To describe the ocean surface bio-optical state, we have utilized estimates of the diffuse attenuation coefficient of ocean water, as a parameter indicative of water quality in terms of light propagation characteristics. This parameter is specifically related to the depth of the euphotic zone and to plant pigment concentration (Smith and Baker, 1978a/b). To gain a perspective on the bio-optical "climate" of the region, we chose to perform some simple statistics of this parameter on a seasonal basis. The data set was divided according to the typical classification in three main oceanographic phases first suggested by Skogsberg (1936) for the Monterey Bay area: the upwelling period, from March to August, the oceanic period, of September and October, and the Davidson Current period, from November to February. The marine climate (with its associated biological cycles) described by these seasonal periods is essentially the result of a variable water flow, induced largely by the prevailing winds. In spring-summer, persistent northwesterly winds correspond to a mainly southward surface flow, accompanied by intense episodes of coastal upwelling. A period of weak and variable winds in fall is marked by the predominance of oceanic conditions in the surface layer. In winter, southerly winds are associated with the Davidson Current flowing northward and impinging on the coast. This seasonal classification reflects in a broad way the oceanographic conditions and events occurring over most of the California coastal region north of Pt. Conception (Bolin and Abbott, 1963; Wooster and Reid, 1963).

In the following we will present a descriptive analysis of the set of seasonal maps that were derived, in terms of dynamical and biological variability in the California Current System.
2. CZCS imagery selection and processing

The data base utilized for the present experiment consisted of 73 images of the California coastal region, collected by the Coastal Zone Color Scanner (CZCS) on board the Nimbus-7 satellite (Hovis et al., 1980), over the years 1981, 1982 and 1983. The temporal distribution of the images, subdivided by month, and within each month in three 10-day periods, is shown in Figure 1.

To describe the ocean surface color field, the images were corrected for atmospheric contamination, and the values of the diffuse attenuation coefficient of sea water at 490 nm, $K(490)$, derived from the ratio of upwelling radiances at 443 and 550 nm. The algorithms adopted for these tasks have been described in detail by Smith and Wilson (1981) and by Austin and Petzold (1981). Since the techniques used to derive chlorophyll estimates from CZCS data are generally based on the same spectral ratio, an indicative relationship between the obtained $K(490)$ values and phytoplankton pigment concentration can be plotted, as in Figure 2 (for the case of waters with pigment concentration below 5.4 mg/m$^3$; R. W. Austin, personal communication).

Subsets covering the central California near-coastal area were extracted from the images and geometrically corrected (Wilson et al., 1981) to obtain new pixel arrays with uniform spacing, fitted to a Mercator projection centered at $36^\circ$ 30' North and $122^\circ$ 45' West (Fig. 3). Three such subsets, which illustrate the nature of the original data for each of the seasonal periods considered, for 1981/1982, are shown in Figure 4, (a) through (c). The remapped arrays (of 256 x 256 pixels, with a pixel size of approximately 1 km$^2$), were then grouped according to the seasonal divisions of Table 1, enabling us to perform some simple time series analysis, on a pixel by pixel basis. Maps of the "seasonal mean" of $K(490)$ were obtained by averaging together pixel values at corresponding locations, with a weight determined by the occurrence of
clouds over each location (i.e., zero for "cloud" pixels, one for "water" pixels). Maps of the "seasonal variance" of K(490) were subsequently derived. Note that, due to the small number of images available for each season and their irregular distribution in time (and the relative bias of the data toward those weather events that produced cloud-free periods), these means and variances must be interpreted as only crudely representative of the real statistics of K(490).

From the analysis of the histograms of the various images, we identified the mean K(490) values typical of the near-coastal and offshore areas, as well as the minimum and maximum variance values, for each seasonal map, and thereby classified the range of values between the two extremes with the thresholding shown in Figure 5. In determining this classification, special attention was devoted to maintaining and actually enhancing the major frontal features that appeared in the images. The values of the mean images were subdivided into 5 intervals of equal amplitude. The first four intervals identify "coastal" waters (2 classes, with the highest K(490) values), "transition" waters (1 class, broken into 3 subclasses) and "open ocean" waters (1 class, with the lowest K(490) values), while the fifth comprises masked areas where data were too sparse or unavailable, and land areas. The values of the variance images were subdivided with a logarithmic scale of 6 intervals of equal amplitude.
Plots of the classification scheme and its normalized distribution function versus time illustrate the seasonality of the range of values and the area occupied by each class identified in the mean K(490) images (Fig. 6). Relative maxima of the values typical for most of the water types considered occur in the spring-summer periods, while relative minima occur in the winter periods. Accordingly, coastal waters have maximum extension in spring-summer and minimum extension in winter, while open ocean waters occupy the least area in spring-summer and the most area in winter. Analogous plots for the K(490) variance images (Fig. 7) present a similar situation. Again, relative maxima in variance are typical of spring-summer, and relative minima are typical of winter. However, no obvious seasonality appears in the normalized distribution function plot, which shows the area occupied by minimum variances decreasing from 1981 to 1982 and then reaching the largest extent in 1983.
Figure 4. CZCS derived images of K(490). Light tones represent high K(490) values, darker tones lower K(490) values; black denotes masked pixels. The images show three different seasonal situations in 1981/1982: (a) 13 June 1981, spring-summer, (b) 29 September 1981, fall, (c) 29 January 1982, winter.
Table 1. Seasonal divisions of the 73 CZCS images utilized.

<table>
<thead>
<tr>
<th>Season</th>
<th>No. of Images</th>
<th>Date of Images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring–Summer 1981</td>
<td>13</td>
<td>Jun 03/09/13/20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jul 06/07/08/11/12/13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aug 20/26/27</td>
</tr>
<tr>
<td>Fall 1981</td>
<td>13</td>
<td>Sep 17/22/29/30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oct 01/05/08/11/12/14/16/18/28</td>
</tr>
<tr>
<td>Winter 1981–82</td>
<td>8</td>
<td>Nov 02/18/30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dec 01/03/22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jan 08/29</td>
</tr>
<tr>
<td>Spring–Summer 1982</td>
<td>7</td>
<td>Apr 19/21/28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>May 23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aug 10/26/30</td>
</tr>
<tr>
<td>Fall 1982</td>
<td>12</td>
<td>Sep 28/29/30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oct 03/04/05/06/07/10/11/12/17/28</td>
</tr>
<tr>
<td>Winter 1982–83</td>
<td>4</td>
<td>Nov 03/13/14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dec 07</td>
</tr>
<tr>
<td>Spring–Summer 1983</td>
<td>13</td>
<td>Apr 03/13/25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>May 06/17/18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jul 03/09/15/17/19/25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aug 04</td>
</tr>
<tr>
<td>Fall 1983</td>
<td>3</td>
<td>Sep 02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oct 17/25</td>
</tr>
</tbody>
</table>

Figure 5. Classification code adopted for (a) seasonal means and (b) seasonal variances of \( K(490) \).
A general trend of decreasing values over time is also shown by both means and variances, with a substantial drop from the spring-summer 1981 values to those of the following corresponding seasons. This variability may reflect real interannual fluctuations of the characteristics of the surface color field, but may also be an artifact introduced by the processing algorithms adopted. The fact that images from summer months only were used for the 1981 spring-summer statistics, and images from both spring and summer months contributed to the 1982 and 1983 spring-summer statistics, did not appear to be significant, since the K(490) values had a comparable magnitude for all the images throughout every seasonal period. We suspect that the observed
trend might be related to the adjustments applied in the process of atmospheric correction of the images, to account for the degradation in sensor response that has affected CZCS (particularly the blue—443 nm—channel) after its first year of operation (Gordon et al., 1983; Hovis et al., 1985). Overcorrecting for sensor decay would, for example, generate values too high for the upwelling radiance in the blue spectral band, leading to higher blue/green radiance ratios and consequently lower $K(490)$ values.

Other effects, related to either atmospheric or oceanic phenomena, could also contribute to the decrease over time of means and variances, as well as to the corresponding increase over time in the areal extent of lower means and variances. A factor that should be taken into account, and that we cannot quantify at this time, is the effect that the El Chichon volcanic eruption of March/April 1982 had on the atmospheric optical properties in the following months (Hoecher et al., 1985). If the atmospheric conditions, following the spring of 1982, were so anomalous as to require special adjustments of the procedure used to remove their influence from the satellite imagery, then our application of an unchanged algorithm for the entire data set could have produced biased estimates of ocean leaving radiances in the period following the eruption. Further, the variability of 1982 and 1983 statistics may also relate to the occurrence of the El Niño event, which began affecting the environmental conditions (and consequently the surface optical properties due to phytoplankton concentration) off the California coast by the end of 1982 (Fiedler, 1984).

3. Seasonal mean and variance images

Figures 8 through 15 show the maps of the seasonal mean (a) and corresponding variance (b) of $K(490)$ that we have obtained for the periods considered. The maps are color-coded according to the classification previously described, which corresponds to the scales imbedded in each image (numerical estimates of the intervals' minimum and maximum values can be retrieved from Figs. 6 and 7). In the mean images, white tones correspond to the highest values of $K(490)$ and darker tones to the lowest values. Similarly, in the variance images, white tones represent the largest variance and darker tones the smallest. In both image series, land masses and areas where data were unavailable appear black. Uncertainties in the definition of the coastlines, which in some images seem slightly distorted, are due to the remapping algorithm that, generally, cannot navigate within an image with a precision higher than plus or minus one pixel. Also, the edges of the maps sometimes appear rather confused, due to the fact that some of the individual images contributing to each seasonal estimate covered a larger area than others. Such boundary areas represent statistics performed on just a few pixels, and were discarded from the interpretation of seasonal patterns.

The spring-summer 1981 maps present a broad band of coastal waters, extending considerably offshore and modulated at its outer edge by numerous south-westward
Figure 8. Spring-summer 1981: seasonal (a) mean and (b) variance of K(490). The images are color-coded according to the scales of Figure 4. Numerical values for the limits of each class appear in Figures 5 and 6.
Figure 9. Fall 1981: seasonal (a) mean and (b) variance of $K(490)$. The images are color-coded according to the scales of Figure 4. Numerical values for the limits of each class appear in Figures 5 and 6.
Figure 10. Winter 1981–82: seasonal (a) mean and (b) variance of K(490). The images are color-coded according to the scales of Figure 4. Numerical values for the limits of each class appear in Figures 5 and 6.
Figure 11. Spring-summer 1982: seasonal (a) mean and (b) variance of $K(490)$. The images are color-coded according to the scales of Figure 4. Numerical values for the limits of each class appear in Figures 5 and 6.
Figure 12. Fall 1982: seasonal (a) mean and (b) variance of $K(490)$. The images are color-coded according to the scales of Figure 4. Numerical values for the limits of each class appear in Figures 5 and 6.
Figure 13. Winter 1982–83: seasonal (a) mean and (b) variance of K(490). The images are color-coded according to the scales of Figure 4. Numerical values for the limits of each class appear in Figures 5 and 6.
Figure 14. Spring-summer 1983: seasonal (a) mean and (b) variance of K(490). The images are color-coded according to the scales of Figure 4. Numerical values for the limits of each class appear in Figures 5 and 6.
Figure 15. Fall 1983: seasonal (a) mean and (b) variance of K(490). The images are color-coded according to the scales of Figure 4. Numerical values for the limits of each class appear in Figures 5 and 6.
The patterns of mean values and variance are quite similar, but while the highest means are concentrated along the very near-coastal area, especially north of Monterey Bay, the largest variances tend to be located somewhat more offshore, indicating a persistent regime of higher \( K(490) \) values along the coastline, with a fluctuating offshore boundary. Note that these images correspond to a period usually associated with intense coastal upwelling and maximum inshore reach of southward flow in the California Current System (Hickey, 1979; Huyer, 1983). In the fall 1981 maps, the band of coastal waters is reduced, and the whole area covered has a rather patchy appearance. High mean values are present offshore from the Pt. Montara/Pigeon Pt. and Pt. Pinos/Pt. Sur areas. Mean values similar to those of coastal waters, possibly associated with the offshore mesoscale eddy field, are also detectable in the southwest part of the image. High variances are generally located offshore. The winter 1981–82 maps also have a rather noisy appearance (due, in part, to some residual atmospheric contamination of the oceanic signal at the edges of clouds), but lower mean values typical of open ocean waters can clearly be seen much closer to the coast than before. The near-coastal area is still characterized by high values of both mean and variance, and so is the area southwest of Pt. Sur, where a wedge-shaped feature that occurs again in fall and winter is detectable. Note that, in this period, the northward flowing Davidson Current should affect the coastal region, and be coupled with a reduced southward flow in the offshore region (Hickey, 1979; Huyer, 1983).

The spring-summer 1982 maps present a quite different situation. The entire northern half of both images is occupied by a large-scale pattern that branches westward from the Pt. Montara area, but that also has a major component in the offshore part of the image. The high mean values and variances of this pattern may be interpreted in terms of "coastal" waters entrained in a very active mesoscale eddy field that, apparently, dominated the surface color variability in this period. Interestingly enough, sizeable patches of open ocean waters are present (quite persistently, as testified by their small variance) just off Monterey Bay and south of Pt. Sur, where the usual coastal band of high mean values and variances has virtually disappeared. An analogous, if weaker, situation is described by the fall 1982 maps. The high mean values in the northern half of the image still appear to define the features of the preceding spring-summer, and lower mean values are still seen very close to the coast in the southern half. The highest variances, though, now appear in the offshore area west of Pt. Sur. In the winter 1982–83 maps, the features that persisted throughout most of the year have disappeared almost completely. The mean image presents high values in several local plumes along the coast, especially between Pigeon Pt. and Pt. Pinos, and around Pt. Sur, as well as extensive open ocean waters, in a pattern very similar to that of the previous winter. The variance distribution in the coastal region is also reminiscent of the 1981–82 winter, but a large patch of high variance is now present in the southwest corner of the image. The features west of Pt. Montara, then, are partly
contaminated by some residual noise effects due to extensive cloud cover over that area, which was present in some of the CZCS scenes utilized to compute these seasonal maps.

In the spring-summer 1983 maps, the broad band of coastal waters observed in 1981 appears again, although characterized this time by less convoluted offshore boundaries. In this season, the highest mean values of the near-coastal area north of Monterey Bay correspond to the highest variances, while the frontal features associated with the high variance area around Pt. Montara correspond quite well to those observed in the previous spring-summer. The ambiguous trend in the quantitative estimates of $K(490)$ reported before prevents us from confirming the general decrease of phytoplankton pigment concentration in the surface layer described by Fiedler (1984) as a consequence of the El Niño event. For the images of this period, we can only make the observation that apparently lower means and variances, and a slight increase in the area characterized by the lowest values of both these parameters, are accompanied by a generally smoother appearance of frontal features and transitions between water types. However, the degree of interannual variability observed in our data set is so pronounced, that we cannot distinguish any macroscopic effect of the 1982–83 El Niño event from that signal. The following fall 1983 maps present an almost winter-like situation, with a reduced coastal band of high means and variances, plus the usual coastal plumes north of Monterey Bay and the wedge-shaped feature off Pt. Sur.

4. Variability of the surface color field

In general, the seasonal maps describe conditions of greater variability in the surface color field (i.e. more pronounced, extensive and convoluted surface features) in the spring-summer periods, followed by an intermediate stage in fall and much reduced variability in the winter periods. The patterns seem, at least from a qualitative point of view, to correlate from season to season within every year, as if a complex structure developed each spring-summer and progressively decayed in time to reach more homogeneous winter conditions. This consistent seasonal trend is apparently unaffected by the high degree of interannual variability most evident in the spring-summer conditions.

Considering that the surface color field is chiefly determined by the contribution of planktonic agents to the surface optical properties, the observed situation reflects seasonal maxima of chlorophyll-$a$ concentration (usually taken as a measure of phytoplankton biomass, in productivity studies; Platt et al., 1975) in spring-summer. Since phytoplankton abundance in this region is generally limited by variations of nutrient concentrations in the euphotic zone, this points to a seasonally modulated nutrient flux into the surface layer. For the California coastal region, spring-summer productivity maxima have been associated with the persistence of predominantly northerly winds, which trigger intense pulses of coastal upwelling and, consequently, a
progressive enrichment of surface waters with nutrients from deeper layers (Smith, 1968; Ryther, 1969; Cushing, 1975; Bakun et al., 1974). The chemical and biological variability generated by offshore Ekman transport affects primarily a coastal region with an offshore scale on the order of the internal Rossby radius of deformation (i.e. about 10–30 km over the continental shelf along this coast). Thus, the direct influence of active upwelling generally appears to be restricted to a narrow coastal band of the order of tens of kilometers, but the region presenting characteristics reminiscent of this coastal area can extend at times more than a hundred kilometers out to sea (Huyer, 1983).

The waters classified in our imagery as “coastal” type indeed extend with scales of these orders of magnitude. However, they appear throughout every season examined, virtually everywhere along the coastline and in striking correspondence with the bottom topography, especially over the continental shelf. Figure 16, (a) through (h), shows a qualitative comparison between ocean color structure and bottom topography. The nearshore patterns (comprised of the first of the two classes designated as coastal waters) are consistently bounded within the 100 fathoms isobath in spring-summer, and recede to the 30 fathoms isobath in winter. The outer band of coastal waters (second of the two classes), while still confined over the continental shelf edge in the fall and winter images, extends much farther offshore in the spring-summer images, either with a highly convoluted boundary (as in 1981), or in plume-like meandering form (as in 1982), or in a fairly homogeneous way (as in 1983). This fluctuation of the coastal layer size could be evidence of the influence of wind-driven upwelling on the nearshore regime. However, together with the enhanced and broadened coastal layer, the “upwelling” period (spring-summer) statistics also show a peak in both mean and variance values for most water types, compared to the other periods, suggesting a seasonal change in surface characteristics for the entire California Current System and not just for the nearshore area.

Persistent nearshore structures, frequently associated with the local bathymetric profile, are quite common in visible and infrared imagery of continental margins, where several phenomena (besides wind-driven upwelling) have been observed to drive trophic enrichment responsible for high plankton concentrations. Interaction of seasonal currents with shelf bottom topography, shelf edge upwelling driven by alongshore currents, continental shelf waves controlled by shelf bottom topography and baroclinic structure, and high speed tidal currents over shallow bottom topography, have all been documented to provide enrichment mechanisms leading to the recurrence of rich patches at the same locations (see e.g. Freeland and Denman, 1982; Marra et al., 1982; Brink et al., 1983; Ikeda et al., 1984; Bowman et al., 1981). A suite of physical processes is then eligible to contribute in maintaining the semi-permanent coastal features illustrated in Figure 16, regardless of the season. The coupling of advective and mixing fields to regional bathymetric patterns, is most evident over the broad shelf north of Monterey Bay, as well as around Pt. Sur. In particular, high K(490) values recur in every season examined on the shelf between Pigeon Pt. and Pt.
Montara, and a wedge-shaped feature appears mainly in fall and winter off Pt. Sur, constantly bounded by the 500 fathoms isobath to the north and the Sur canyon and Lucia canyon system to the south. Similarly, the frequent occurrence of waters with open ocean characteristics, or at least lower K(490) mean values, in the area off Monterey Bay, is probably linked to the strong influence of the Monterey submarine canyon system on the local circulation (Broenkow and Smethie, 1978).

Offshore structures, identified by "coastal" and primarily "transition" water type characteristics, also appear in virtually every season in the mean images, possibly in
relation to the variability of the offshore mesoscale eddy field, and not just to
fluctuations of coastal phenomena alone. The occurrence and irregularity of high
variance patches in the offshore region, especially suggests the development and
transition of mesoscale features linked to California Current System dynamics, on a
space scale of up to a hundred kilometers and on a time scale of months. In
spring-summer, the pronounced variability in the offshore zone is connected to the
enhanced and broadened coastal layer and, moreover, accompanied by seasonal
maxima of both means and variances for most water types. In their analysis of the
temporal correlations between physical and biological fluctuations in the California
Current System, Chelton et al. (1982) attributed most of the interannual variability in
productivity to nutrient fluxes related to variations in intensity of the California
Current flow, rather than to local and episodic coastal wind-driven upwelling. They
suggested that these fluxes are better explained in terms of either horizontal advection
from high latitudes, or vertical advection into the surface layer associated with
goestrophic tilting of isopycnals, due to variations in the southward flow. The fact that
changes in the seasonal flow patterns might be responsible for large-scale nutrient
regeneration, does provide a sensible, if qualitative, interpretation of the situation we
observed off central California where, in spring-summer, surface southward flow
extends inshore very close to the shelf edge, only to be displaced by the near-coastal
surfacing of deep northward flow (the Davidson Current) in winter (Chelton, 1984).
For spring-summer, then, the peak of California Current strength and influence on the
coastal regime could be associated with a generally richer environment for planktonic
growth (and hence higher $K(490)$ values) and an offshore development of the broader
area occupied by waters with “coastal” characteristics. Further, the conceptual picture
of the instantaneous California Current as an unstable flow, continuously modulated
by mesoscale meanders and shedded eddies superimposed on the large-scale mean
flow, would suggest advective mechanisms able to propagate the effects of extensive
surface phenomena to the scales observed in the imagery. In the summer of 1982, for
example, Mooers and Robinson (1984) observed off Pt. Arena a pair of counterrotat-
ing (northern anticyclonic and southern cyclonic) eddies, which were apparently
advecting offshore a jet-like filament entraining waters of coastal origin (that they
interpreted as recently upwelled, on the basis of the thermal signature). An analogous
feature also appears in their data, in the area off Pigeon Pt., in remarkable
correspondence to the patterns observed in our imagery of that period. Similarly,
Broenkow (1982) reported on another pair of counterrotating (northern cyclonic and
southern anticyclonic) eddies off the Monterey Bay area, between which, in the
summer of 1980, was a region of strong shoreward flow. Pelaez and Guan (1982) also
observed eddy pairs off Monterey in the summer of 1981, and we often noted waters
with open ocean characteristics reaching close to shore in that area. This kind of
pattern is, therefore, not only persistent throughout a season, but also recursive from
year to year, possibly driven by the local basin morphology.

The frontal structures in the mean $K(490)$ maps, as well as in the variance maps (as
Figure 17. Comparison between frontal structures (and variance classes extension) in the K(490) variance images and major bottom topography of the area. Depths appear in Figure 3.

illustrated in Fig. 17), seem to be quite regularly coupled to the bathymetric relief even in deep ocean areas, where the reasons for the correspondence are not as obvious as in coastal, shallower areas. The isobaths of depth between 1000 and 2000 fathoms, for example, usually delineate the outermost reach of waters of coastal or intermediate type over the continental slope. Submarine canyons and seamounts in particular (i.e. the Pioneer Peak and Guide Peak system, the relief at the base of Monterey Canyon, The Davidson Peak system) are often connected to some kind of surface feature, or to a
boundary between different water types. In our interpretation, these surface manifestations of deep obstacles may reflect the interaction of bottom relief with the flow structure throughout the water column, and suggest a profound influence of basin morphology in mediating the effects of mesoscale dynamics in the California Current System on the surface color field.

5. Conclusion

High altitude observations in the visible spectrum have familiarized oceanographers with the high degree of variability of the ocean color field. Satellite images provide assessments of the ocean surface optical properties distribution over large areas with repetitive coverage over short time periods, expanding synoptically the related concept of patchiness in the planktonic environment. Taking advantage of these characteristics of satellite measurements, "climatological" aspects of the ocean color variability can also be investigated, as shown by the present work.

In the area and period examined, the main feature emerging from the analysis of \( K(490) \) means and variances is the seasonality of the values of both parameters, which present relative maxima in spring-summer periods and relative minima in winter periods for most of the water types identified in the images. Moreover, the permanent presence of distinct coastal (i.e. the continental shelf/slope area) and open ocean zones, subject to a seasonal variation in spatial characteristics, is also documented. The coastal layer, identified by high means and often high variances of \( K(490) \), is most developed and persistent in spring-summer, while it has a reduced appearance in fall and especially winter. Offshore features, marked by high \( K(490) \) values, are also most prominent, and connected to the coastal ones, in spring-summer, but can occur in every season, as testified by the high variance patches often encountered away from the coast. Over interannual time scales, the seasonal patterns present large-scale spatial variations in the spring-summer periods, and only local, small-scale variations in the winter periods.

In light of the oceanographic climate of this region, the spring-summer enhancement can be interpreted as a combination of the effects of coastal upwelling, offshore mesoscale dynamics and seasonal variations of the California Current flow. Thus, dynamic processes appear to play a major role in shaping the heterogeneity of ocean color, and hence that of the biological agents on which the color chiefly depends. However, the bathymetry of the basin also seems to have paramount influence on the ocean color variability, possibly through its effects on the water flow characteristics. This influence might be greater than suspected before even in deep water areas.

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REFERENCES


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