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California Current Eddy Formation: Ship, Air, and Satellite Results

Satellite remote sensing combined with conventional tools improves the ability to observe ocean currents.

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Interest in the structure and circulation of the California Current has increased recently. On practical grounds, the prospects of offshore oil drilling in the region and the attendant potential for oil spills make knowledge of this current important. On scientific grounds, oceanographic awareness of and interest in the dynamical significance of meandering and eddying processes in ocean current systems have increased substantially in recent years. The California Current is probably one of the best observed currents in the world. As a result, it is possible to determine its long-term mean state, and contrast it with more transient meanders and eddies embedded in the flow.

The California Current system has been repeatedly surveyed hydrographically by research vessels over the last 27 years, at 1- to 3-month intervals in most years. The 80-kilometer spatial resolution of an established grid of hydrographic stations has frequently been fine enough to show the existence of mesoscale (100 to 300 km) meanders and eddies superimposed on the larger-scale mean flow in the California Current. The time and space resolution of the repeated surveys, by themselves, usually has not been sufficient for the stages of evolution of a meander to be followed in any detail. Satellite-borne infrared scanners of sufficient sensitivity now produce high-quality imagery of sea-surface temperature gradients associated with these meanders. The time and space resolution of this imagery, when combined with concurrent hydrographic data, is sufficient for the important stages of meander development to be observed through to cutoff of separate eddies.

Historical Background

Mean flow of the California Current. Since 1949 the California Current has been the subject of intense observation under the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program (*1*). The mean geostrophic current shears for the month of March, as determined by 16 years of hydrographic data, have been analyzed (*1*) and are reproduced in Fig. 1. Here the mean dynamic topography of the surface relative to the 500-decibar surface (1 decibar of pressure is equivalent to approximately 1 meter of water depth) shows a maximum current of 5 to 10 centimeters per second directed south parallel to the coastline. Approximately 80 percent of the current shear in the vertical is concentrated in the upper 200 m, as indicated by similar analyses of current shear between 200 and 500 dbar. The shear of 500 dbar relative to 1000 dbar is insignificant.

Mean horizontal sections of temperature and salinity at a depth of 150 m (*2*), reproduced in Fig. 2, a and b, show that the shallow flow parallel to the coast is associated with seaward increases in temperature and decreases in salinity. Mean vertical sections of temperature and salinity (Fig. 2, c and d) illustrate how these gradients are strongest in the upper 300 m. Figures 1 and 2 complete what is a consistent and straightforward picture of a mean circulation in geostrophic balance.

Mesoscale variations in the California Current. The fairly broad, smooth picture of the mean flow of the California Current is, in fact, hardly ever realized in any one hydrographic survey. The actual flow is typified by the January 1965 CalCOFI analysis of the surface dynamic topography relative to 500 dbar (Fig. 3a). Here, the California Current resembles a narrow (150 km) meandering jet. The scale of the meanders ("wavelength") is 300 to 500 km, and the intensity of the flow can reach 20 to 40 cm/sec. The associated sea-surface temperature patterns from this typical survey (Fig. 3b) conform to these mesoscale variations as alternating warm and cold "tongues" having temperature contrasts of 1° to 3°C. The 80-km spatial sampling of the CalCOFI grid makes it difficult to determine to what degree the surface temperature patterns are simply reflecting the variable depth of the main thermocline, and to what degree they are determined by surface advection of the large-scale surface temperature field by the mesoscale current field. In the former case, mesoscale variations in the surface temperature and main thermocline would be in phase, with colder (warmer) surface water overlying colder (warmer) main thermocline water. In the latter case, the variations would be 90° out of phase, with warmest and coldest surface waters overlying the regions of maximum horizontal temperature gradient in the main thermocline.

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The repetition interval for CalCOFI surveys has been variable between 1 and 3 months. There have been a few occasions where a sequence of monthly surveys has been performed that shows the time development of mesoscale variations. The 4-month sequence from April to July 1952 (Fig. 4) reveals the development of several such circulation features. In particular, note the intensification of cyclonic circulation near 28°N,117°W, 100 to 200 km west of Punta Eugenia, over the interval. Another feature, an anticyclonic ridge, strengthens near 32°N,120°W, 300 km south of Point Conception. The latter feature is associated with an inshore-directed intrusion of warm, low-salinity water.

It is clear that the 80-km and 1-month space and time sampling interval is frequently too coarse to follow the detailed development of these features. On at least one occasion (*3*) additional measurements made from a research vessel have provided a finer picture of eddy development. Nevertheless, the regular CalCOFI surveys are still made with this sampling scheme, but the description of these mesoscale circulations may now be augmented by data from satellite-borne sensors.

Satellite Radiometer Background

There has been a steady improvement in the quality of earth-orbiting scanning radiometers over the last several years, and they have reached the point where oceanographically useful information on the horizontal gradients in sea-surface temperature may be obtained.

The very high resolution radiometer (VHRR) of the NOAA-3 satellite is the highest-quality infrared scanner orbited to date. It travels in a near-polar orbit 1500 km high, providing potentially global coverage twice per day. The VHRR has 1-km spatial resolution and is a two-channel device, viewing in the visible (VIS, 0.6 to 0.7 micrometer) and thermal infrared (IR, 10.5 to 12.5 micrometers) portions of the spectrum simultaneously. For the IR, the noise equivalent differential temperature (NEDT), which expresses the overall system sensitivity, is about 0.5° to 1.0°C when viewing the ocean surface. Thus the sea-surface temperature difference between two adjacent 1-km areas viewed by the scanner may be resolved if it is larger than the scanner system's NEDT. For larger areas, temperature differences smaller than the NEDT may be measured, because many of the noise sources are of a random nature and may be suppressed by appropriate averaging. More background on the VHRR instrument is given in (*4*).

It should be emphasized that the radiometrically determined temperatures from the VHRR may be made quantitative and reliable. The instrument is calibrated over its full range before launch and provides a two-point calibration on every scan after launch. There are about seven horizon-to-horizon scans per second. Thus uncertainties in the measurement of the horizontal sea-surface temperature gradient arise not so much from the instrument as from viewing the sea surface in the presence of clouds and through the intervening atmosphere. For the latter effect, methods have been devised to correct the available two-channel radiometer data to absolute sea-surface temperature (*5*).

These methods rely on externally supplied information on the vertical distribution of temperature and humidity in the atmosphere, which is generally available from radiosondes but at widely separated points, and on the assumption of uniform atmospheric conditions between observing points. Cloud effects are eliminated through inspection of the visible channel or through statistically based schemes that rely on the single infrared channel alone (*6*). For the purposes of this study, however, true horizontal gradients in sea-surface temperature are identified subjectively, mostly on the basis of the great multiweek time persistence of mesoscale ocean structures compared with the rapidly changing atmosphere.

In early 1974 the National Environmental Satellite Service, part of the National Oceanic and Atmospheric Administration (NOAA), established a satellite

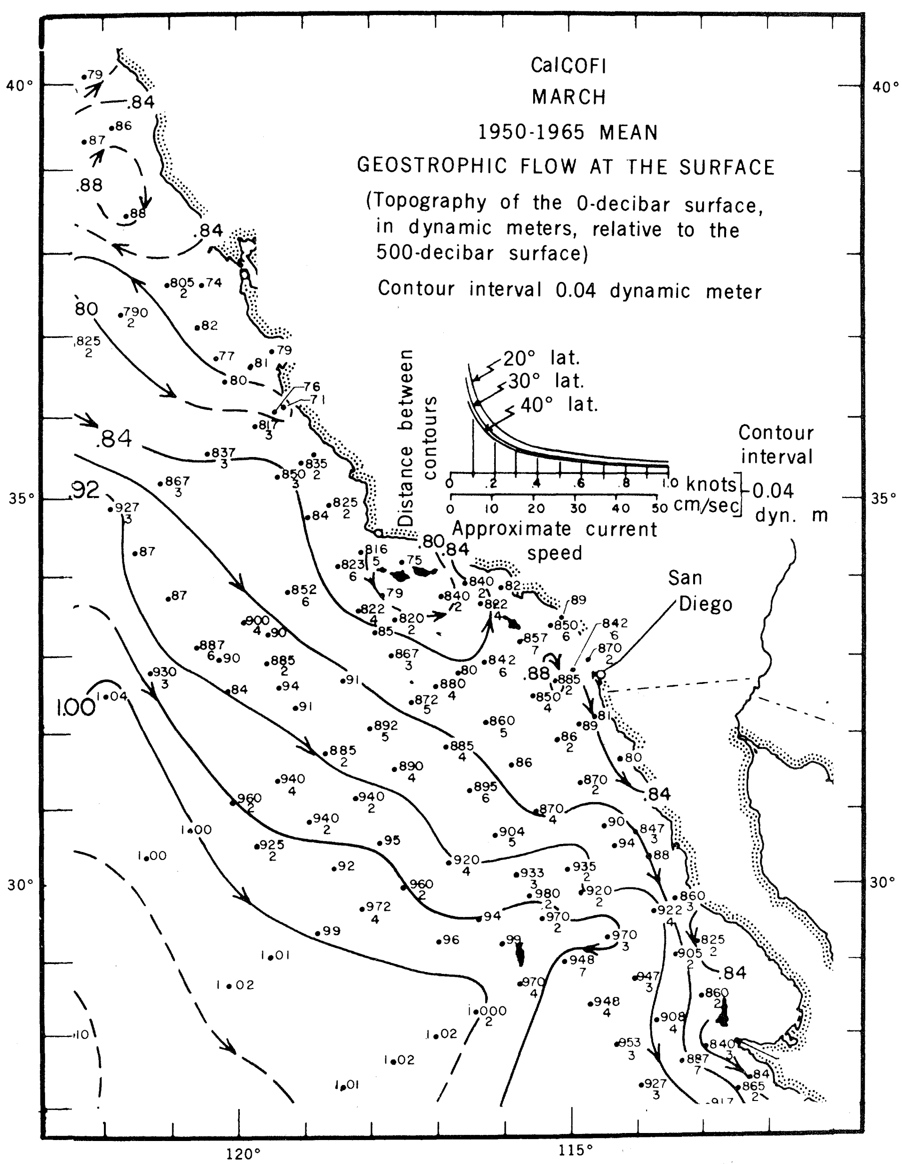
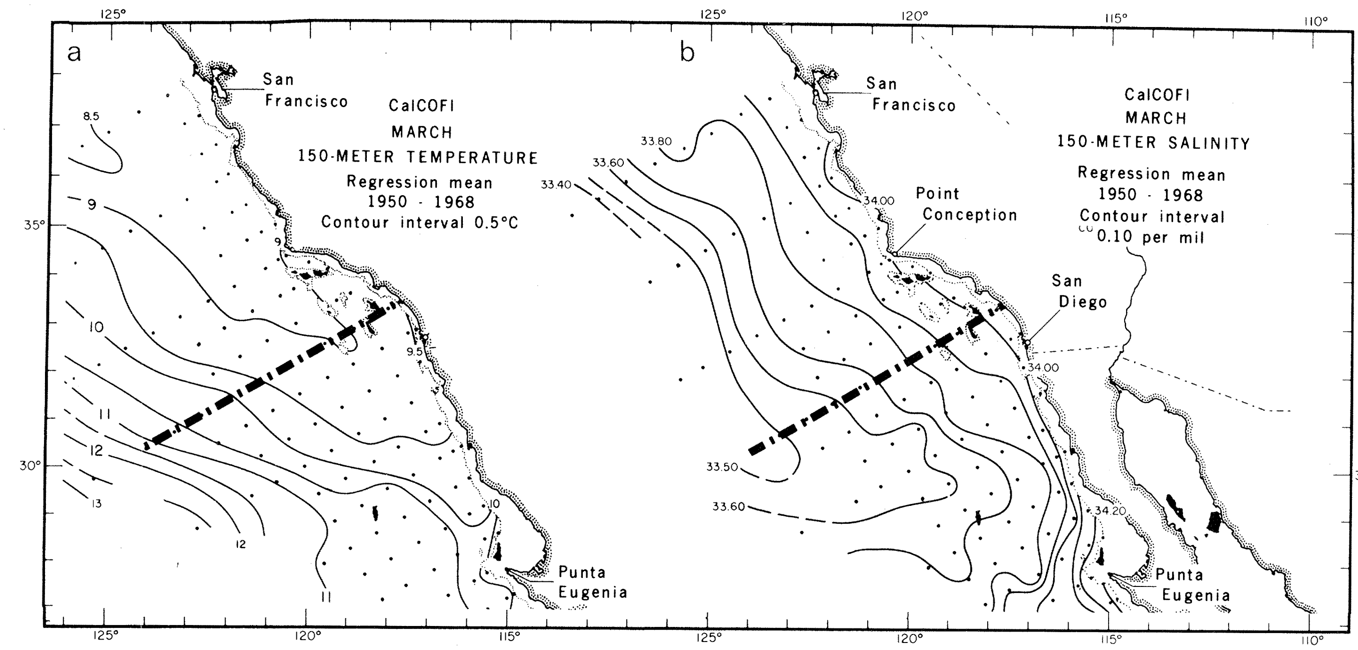


Fig. 1. Long-term mean dynamic topography of the California Current, constructed from 16 years of March CalCOFI hydrographic data (*1*).

field service station at Redwood City, near San Francisco, California. This station is equipped to receive the analog VHRR data transmission directly from the NOAA satellites, convert it to digital form, and store the data on computer magnetic tape. For the infrared channel the digitization scheme results in a least-count interval of approximately 0.7°C in the range of sea-surface temperatures. The magnetic tapes may be played back into a photo-display device through a



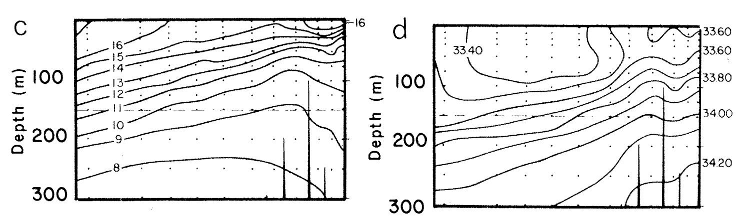


Fig. 2. (a and b) Long-term mean temperature and salinity at a depth of 150 m covering the California Current. (c and d) Long-term mean temperature and salinity along vertical section indicated in (a) and (b) (2).

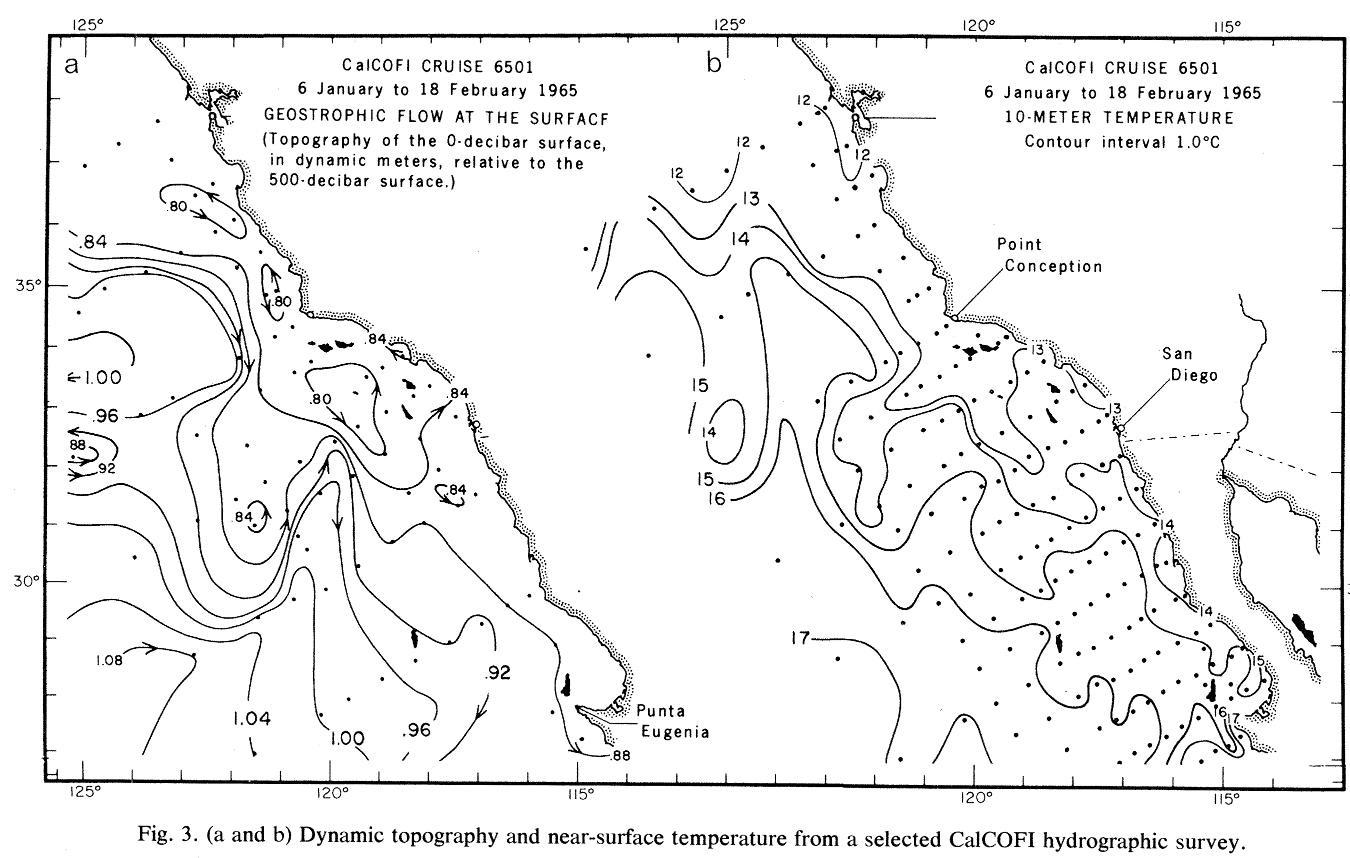


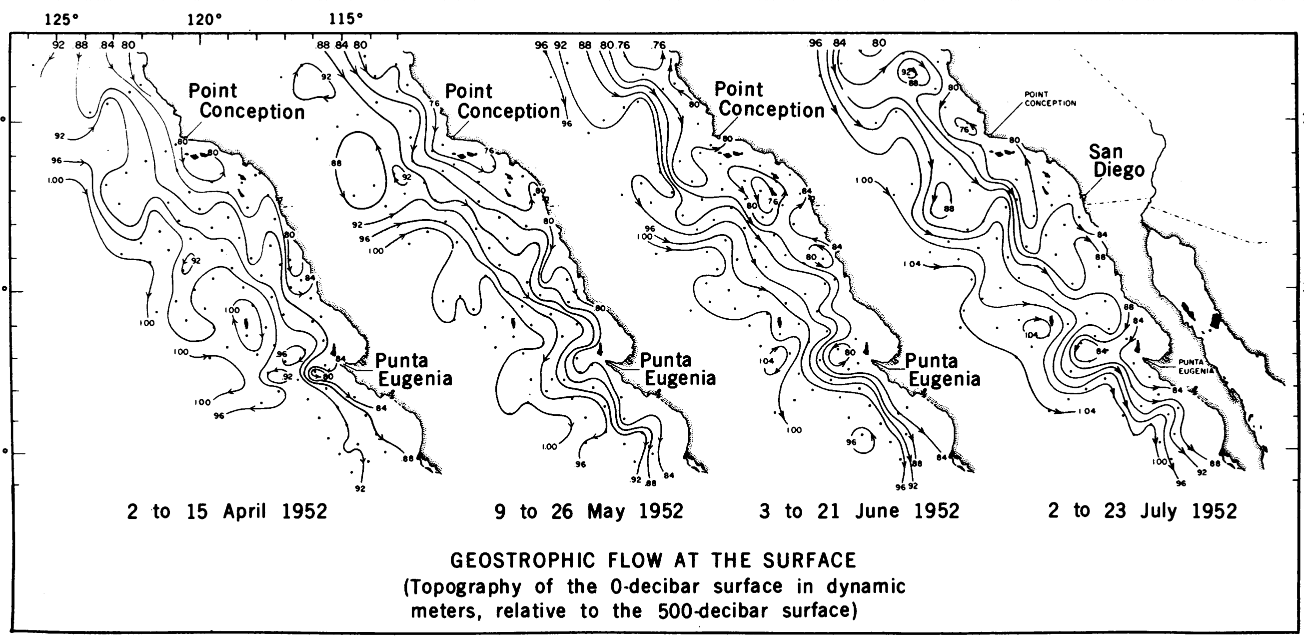
Fig. 3. (a and b) Dynamic topography and near-surface temperature from a selected CalCOFI hydrographic survey.

minicomputer holding any chosen look-up (enhancement) table, so that a range of gray shades corresponds to a selected range of sea-surface temperatures.

The establishment of the field station at Redwood City provided an ideal opportunity for investigating the California Current. It provided ready access to the highest-quality thermal infrared scanner data, in a region frequented by clear, dry continental air masses, which offer the best conditions for viewing the sea surface. This, combined with the extensive historical data and the continuing data from CalCOFI surveys, increased the chance for successful correlation and interpretation of data from ship- and satellite-based sensors.

Satellite Radiometer Results

On several occasions during early 1975 dry, relatively cloud-free continental air flowed toward the west and south out over the California Current. Figure 5 shows the NOAA-3 VHRR imagery from both channels in the region near Point Conception, for daytime passes on 21



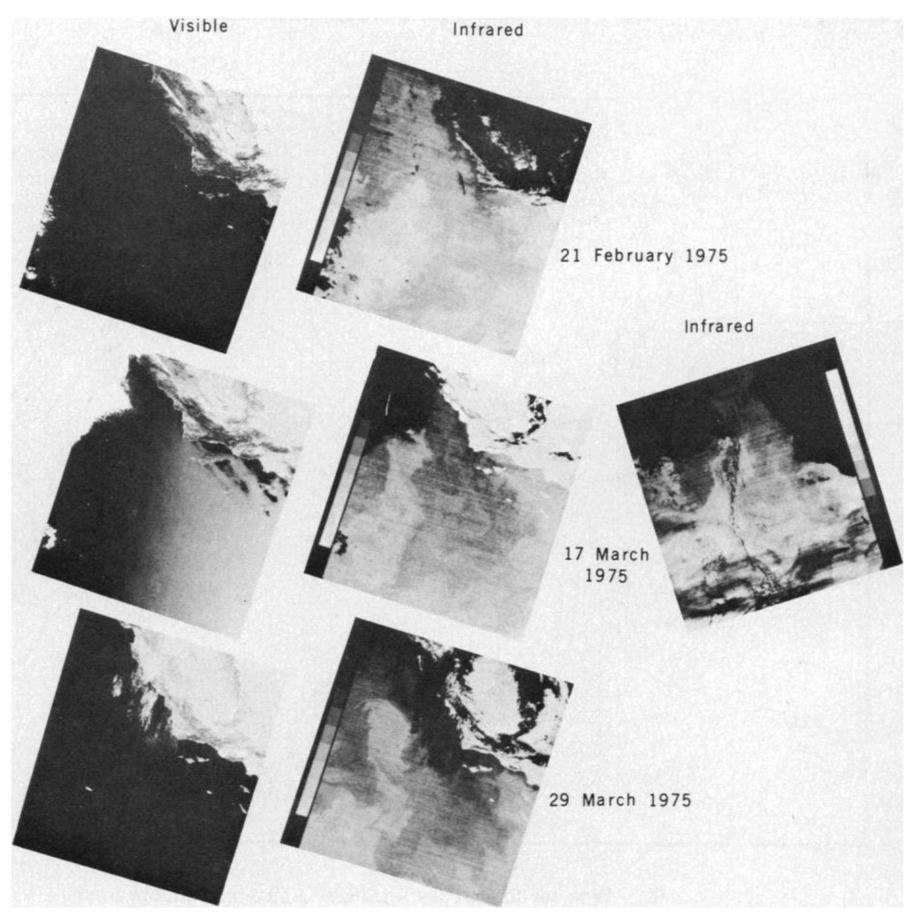


Fig. 4 (above). Sequence of maps of dynamic topography from four CalCOFI surveys of the California Current, April to July 1952. Fig. 5 (right). NOAA-3 satellite VHRR scanner data for three relatively cloud-free days in February and March 1975, from Monterey Bay to Los Angeles, California (north is toward the top). The nighttime infrared image (far right) for 17 March 1975 shows the topmost portion of a warm (light color) intrusion of water obscured by cloud in the previous daytime pass. The image for the same date in the visible channel shows the effect of sun glint in the eastern portion. The sea surface in the lee of islands and near shore is more protected from prevailing wind and does not scatter sunlight into the scanner.

February, 17 March, and 29 March 1975. The 17 March nighttime pass, 12 hours after the daytime pass, is included to reveal portions previously obscured by cloud. Each image is 768 km by 681 km in size. The visible channel data have been enhanced to bring out all clouds clearly. The infrared data have been enhanced to cover the full 7°C range of sea-surface temperature sensed by the radiometer. In this enhancement the warmest areas are encoded white, the coldest black. The gray scale wedges attached to the infrared images show 11 0.7°C temperature steps spanning the full range. Note that all clouds are colder than the sea-surface temperature and are therefore encoded black.

The major feature to observe in Fig. 5 is the warm region of sea-surface temperature entering from the southwest on 21 February, which develops into an elongated shape veering north along the coast by 17 March. The pinch-off of the northernmost portion of this feature is, in fact, realized on 29 March. The clear frontal boundaries that delineate the evolution of this feature have been transferred for clarity to Fig. 6.

Historical CalCOFI data, such as those discussed above and displayed in Fig. 4, seem to suggest that the VHRR was imaging an anticyclonic meander or intrusion of warm, low-salinity offshore water, which then developed into a cutoff anticyclonic eddy. Fortunately, a CalCOFI hydrographic survey took place in this region between 1 and 9 March 1975. The temperature and salinity distributions at various depth levels that were observed in the survey are shown in Fig. 7, along with the dynamic height of those levels relative to 500 dbar.

The survey distribution of surface temperature coincides particularly well with the 21 February VHRR data, and further shows that the warm surface temperature pattern exists down to 250 m and is accompanied by a similar low-salinity pattern. The resulting computed dynamic height pattern shows the anticyclonic circulation of a meander. Maximum surface geostrophic currents (relative to 500 dbar) of 10 to 15 cm/sec are estimated from the dynamic height map. In Fig. 8 the frontal boundaries of 21 February and 17 March determined from the satellite data are superimposed on the surface dynamic topography computed from the hydrographic observations of 1 to 9 March. Figure 8 is thus the oceanographic analog of routine weather charts, which show fronts in a surface pressure analysis.

So far we have concentrated on results related to a particular dynamic feature near Point Conception because, in addition to the satellite coverage, supporting hydrographic data were available. The satellite imagery covers a much larger area. The 29 March imagery of Fig. 5 includes only a small portion of a much larger (1350 km by 2370 km) nearly cloud-free scene, extending from north-

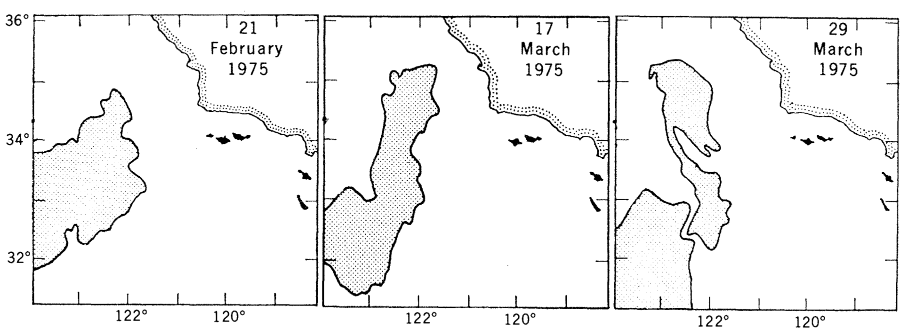
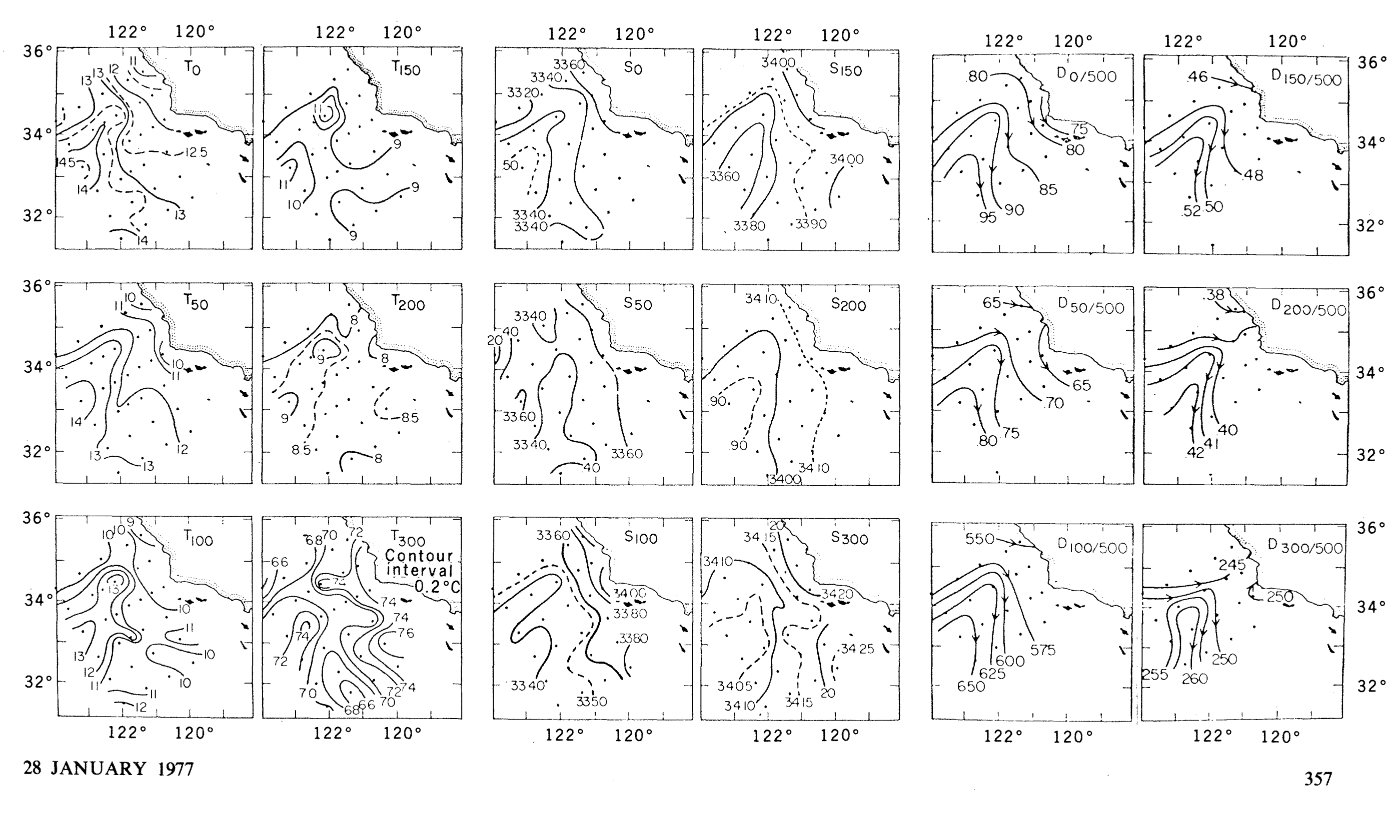


Fig. 6 (left). Development of warm-water intrusion (stippling), as taken from Fig. 5 imagery frontal boundaries. Fig. 7 (below). Distributions of temperature (*T*, °C), salinity (*S*, parts per thousand), and dynamic thickness (*D*, dynamic meters, relative to 500 dbar) obtained from a CalCOFI hydrographic cruise of 1 to 9 March 1975, at depths of 0, 50, 100, 150, 200, and 300 m.



ern California to Guadalupe Island (Fig. 9). The enhanced infrared data in the cloud-free areas provide evidence that the warm meander being cut off near Point Conception is only one of several such features of similar scale extending throughout the California Current.

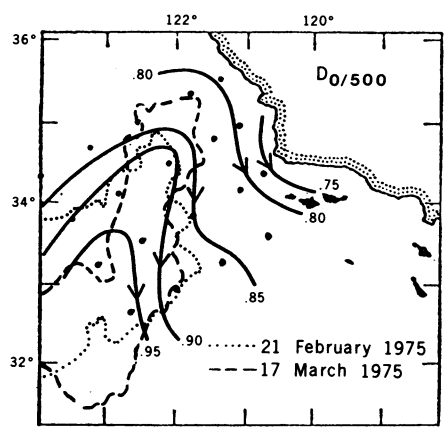
Extended verification of the large number of meanders and other features apparent in Fig. 9 was not possible, since the research vessel hydrographic data were confined to a small subarea. The following year, however, an opportunity arose to obtain subsurface data over a larger area, to be matched against a satellite infrared image.

Figure 10a shows this image, obtained by a Defense Meteorological Satellite Program (DMSP) satellite scanner, whose data were received at a Naval Weather Service facility in San Diego, California. The DMSP scanner (7) is basically similar to the VHRR, the two main differences being that the DMSP scanner receives energy in a wider portion of the infrared spectrum (8 to 13 μm) and the transmitted data are in digital form, with a 1.56°C least count. In Fig. 10a, four of these counts, spanning 4.7°C are displayed as identifiable gray shades, black being coldest. This image, from 13 March 1976, which shows sea-surface temperature frontal structure suggesting strongly developed meanders, was carried along on two flights of a Naval Oceanographic Office P-3 aircraft on 13 and 14 March 1976. The aircraft was used to drop approximately 80 air expendable bathythermographs (AXBT), which provide vertical profiles of temperature to a depth of 350 m. In addition, sea-surface temperature was obtained continuously from an airborne radiation thermometer (ART). The ART and AXBT data were employed to construct temperature distributions at the surface and at a depth of 200 m, as displayed in Fig. 10, b and c. These maps were drawn by an independent analyst who had not previously seen the DMSP imagery. It is clear that the DMSP image provides extensive information on the horizontal gradients of temperature through the upper few hundred meters and may be readily related to the flow of the California Current. From one prominent warm tongue an anticyclonic ridge in the circulation may be inferred, centered at 31°N, 121°W. Similar ridges have occurred in the past, as Fig. 2 shows.

Theory

The consistent picture developing from combined ship and satellite data is that the California Current is an unstable flow, continuously developing meanders with wavelengths of several hundred kilometers, which can intensify over several months and go to cutoff, creating isolated eddies. A rigorous instability analysis is beyond the scope of this work and would require investigation of many factors, such as the configuration of the coastline, the bottom topography, the variations in wind stress, and the barotropic and baroclinic instability created by horizontal and vertical shear in the mean flow.

It can be demonstrated that the simplest baroclinic instability theory approximately predicts the space and time scales that are observed. Tang (8) has developed an analytical solution for the case of a rotating fluid with uniform vertical shear in an upper layer of constant Vaisala frequency, overlying a lower layer with a different Vaisala frequency but no vertical shear. (The Vaisala frequency is the natural frequency of oscillation of a vertical column of fluid given a



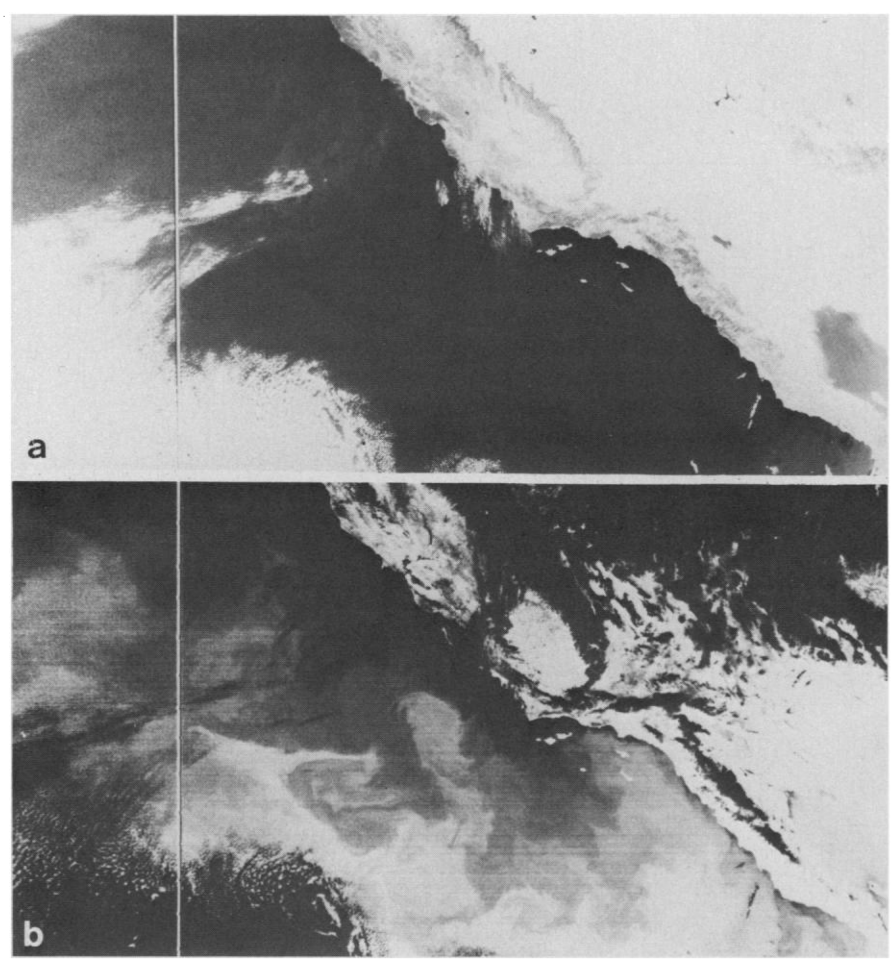


Fig. 8 (above). Reproduction from Fig. 7 of the dynamic thickness of the surface relative to 500 dbar, with superimposed satellite sea-surface temperature frontal boundaries from Fig. 6. Fig. 9 (right). Regional view of the California coast, from northern California to central Baja California, from the NOAA-3 satellite VHRR. Images from both the visible (a) and thermal infrared (b) channels, obtained simultaneously from the radiometer, are shown. The infrared data are enhanced to display horizontal variations in sea-surface temperature in cloud-free areas, with white (warm) to black (cold) corresponding to a 7°C temperature range. Meanders and eddies are apparent throughout the California Current.

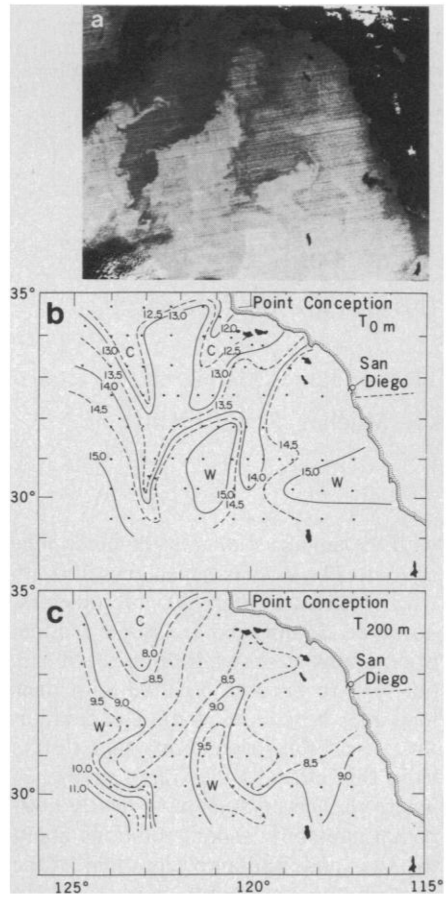


Fig. 10. (a) Defense Meteorological Satellite Program high-resolution thermal infrared image off southern California, 13 March 1976. Clouds in the western portion are coded black. Sea-surface temperatures are coded as in Fig. 9, except that the black-white range covers 4.8°C. (b) Analysis of sea-surface temperature based on air expendable bathythermograph probes, deployed by a Naval Oceanographic Office P-3 aircraft on 13 and 14 March 1976. (c) Same as (b) except that the analysis is of temperature at 200 m.

small displacement from its equilibrium position, and is dependent on the vertical density stratification of the fluid.) Following his notation, we select the following values as typifying the long-term mean baroclinic flow and Vaisala frequency distribution for the California Current: U, the velocity differential between the top and bottom of the upper layer, 0.08 msec^{-1}; H, the thickness of the upper layer, 200 m; N, the Vaisala frequency of the upper layer, 1.5×10^{-2} sec^{-1}; h, the thickness of the lower layer, 4000 m; and n, the Vaisala frequency of the lower layer, 1×10^{-3} sec^{-1}. The solution of Tang yields, for the most rapidly growing instability, a wavelength of 230 km, a (real) phase speed of 0.01 msec^{-1}, and an e-folding time of 98 days. This appears to be within a reasonable factor of 2 to 3 of the observations, considering the limitations of the theory and the data. A similar analysis of growing and traveling waves in the Gulf Stream, also based on satellite imagery, has appeared recently (*9*).

Summary

Until recently, quantitative measurements of the circulation of the California Current were limited to hydrographic determinations of temperature and salinity. This information is now being augmented by satellite data. Clouds permitting, satellite scanner systems can locate major ocean frontal boundaries if they are associated with even quite weak horizontal sea-surface temperature gradients. The satellite data are most usefully interpreted in a region such as that encompassing the California Current, where the surface and main thermocline temperature distributions bear some relation to each other. In such a region, it is possible to make interpretations of circulation based on satellite-derived sea-surface temperature patterns. The correctness of these interpretations depends heavily on the availability of historical and present-day subsurface data, collected by conventional methods from ships and aircraft. Satellite infrared scanners, in addition to providing information on circulation with vastly increased spatial resolution, have the potential (with cooperative weather) for providing increased time resolution. These improvements in resolution have permitted us to see that much of the spatial variation in the California Current takes place along well-defined fronts and to observe the evolution of one particular meander.

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10. We thank J. Bottoms, manager of the NOAA/NESS Redwood City, California, Satellite Field Service Station, and his staff for their assistance. The March 1975 hydrographic data were collected by National Marine Fisheries Service personnel aboard the R.V. *David Starr Jordan*. A. Bainbridge of Scripps provided valuable assistance in accessing these data. J. Wyllie and A. E. Walker provided drafting and other help. We also thank J. Kerling and M. Shenk of the U.S. Naval Oceanographic Office for the opportunity to collect aircraft data. The research reported here was supported by ONR contract N00014-75-C-0260 and NSF contract OCE-75-23361 under the North Pacific Experiment (NORPAX).