COASTAL FRONT OBSERVATIONS WITH AN INFRARED SCANNER

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ABSTRACT

Thermal infrared (IR) images from NOAA environmental satellites and from a helicopter-borne thermal IR scanner were used to study water-mass dynamics in the vicinity of San Onofre Nuclear Generating Station (SONGS). The approach consists of using the satellite images to establish the identity and spatial distribution of oceanographic phenomena and using the helicopter-borne IR scanning equipment jointly with ground truth measurements to obtain increased resolution.

Coastal fronts, ubiquitous yet not readily visible to earthbound observers, were recognized on the satellite thermal IR images as having an elongated shape and being located within a few to several kilometers from the coast. A front emanating from Dana Point, California, divided cool coastal water from warmer water on the offshore side. Thermal IR images obtained from a helicopter revealed the details of two additional front-like structures, or plumes, near SONGS. The fronts are important because they are typically regions of high biological productivity; they also affect dispersion of floatables and buoyant effluent.

The existence of the coastal fronts appears to be linked to coastal upwelling processes occurring in the lee of coastal headlands. This characteristic location suggested that the phenomenon was associated with a raised thermocline at the center of a cyclonic gyre driven by the predominant northwesterly wind. The cool water from the upwelling pockets formed a plume, which advected downwind, displacing the warmer water seaward and creating a coastal front. During the lull in upwelling activity, the front appeared to decrease in size and even disappear entirely.

RESUMEN

Imágenes térmicas IR de satélites NOAA así como de un rastreador termal IR a bordo de un helicóptero fueron usadas para estudiar la dinámica de cuerpos de agua en las cercanías de la Planta Generadora Nuclear de San Onofre (SONGS). El procedimiento consiste en, através de imágenes transmitidas por satélite, establecer la identidad y la distribución espacial de fenómenos oceanográficos usando el equipo de rastreo IR a bordo de helicóptero, unido a mediciones en tierra, para proveer un aumento en la resolución del fenómeno así identificado.

Los frentes costeros, siempre presentes pero no fácilmente visibles, fueron identificados en las imágenes térmicas IR presentando una forma alargada y situados de unos cuantos, a varios kilómetros de la costa. Un frente empezando en Dana Pt., California dividía aguas frías hacia la costa, de aguas templadas del lado opuesto a la costa. Las imágenes termales IR obtenidas desde un helicóptero revelaron los detalles de otras dos estructuras tipo frentes, o plumas, cercanoas a SONGS. La importancia de los frentes para SONGS es que las zonas frontales son típicamente regiones de alta productividad biológica; también afectan la dispersión de elementos flotantes y emanaciones más livianas que el agua.

La existencia de los frentes costeros parece ligada a los procesos de surgencia costera que ocurren a sotavento de las tierras costeras. Esta localización característica surgiere que el fenómeno estaba asociado con una termoclina elevada ubicada en el centro de un giro ciclónico generado por el viento predominante del norte. El agua más fría proveniente de los bolsones de surgencia se desplazó en la dirección del viento, en forma de pluma, desplazando el agua más cálida mar adentro, creando así un frente costero. Por otra parte, durante un relajamíento del proceso de surgencia, el frente disminuyó en tamaño, llegando a desaparecer completamente.

INTRODUCTION

A coastal front frequently appears in the vicinity of San Clemente, California (Figure 1). The coastal front, marked by a discontinuity in the sea-surface temperatures, has been recognized repeatedly on thermal IR images from NOAA satellites collected since 1980 (SCE 1982; SCE 1983). The front extends southeast from Dana Point, passing beyond San Clemente and the San Onofre Nuclear Generating Station (SONGS), dividing a cool water mass adjacent to shore from warmer water offshore. The width of the cool-water band on the shore side of the front varies from 1 to 15 km, with occasional periods during which the front is not observed (Grove and Sonu 1983).

The front's downcurrent range of influence is on the order of 10^1 km or less, thus implying that the front is

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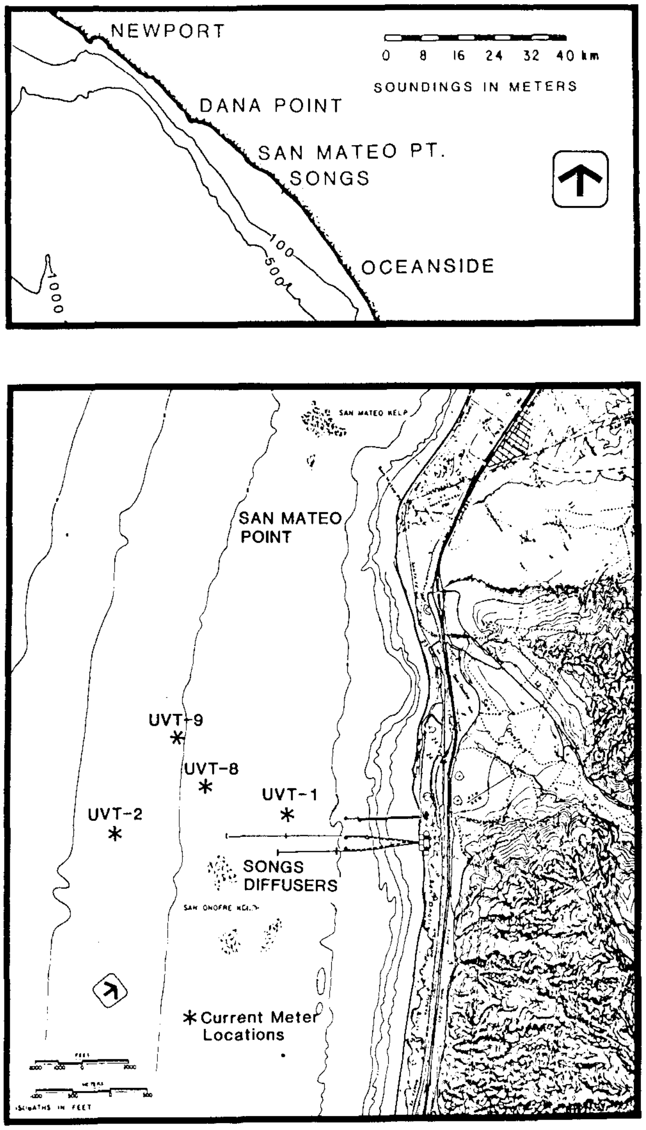

Figure 1. Study location.

submesoscale in size. The processes contributing to the front's characteristics are also submesoscale, since the front appears to be an independent system in the region (Grove and Sonu 1983). The fronts discussed in this paper will be termed microfronts to distinguish them from mesoscale fronts as described by Mooers et al. (1977) and Simpson and Pingree (1977). Although the satellite IR images have been useful for identifying the existence of microfronts, the 1.1-km spatial resolution of the images precluded a detailed description of their characteristics.

The coastal front's importance lies in the fact that there are increased nutrient concentrations as a result of upwelling activity near the front, and consequently increased primary productivity (Mooers et al. 1977). The microfront phenomenon is being studied in the Dana Point to San Onofre region because of the similarities between the biological influences of the localized front and those influences predicted to occur as a consequence of operating the SONGS thermal diffuser system.

Murdoch et al. (1980) predict that on the order of 84,000 tons of additional phytoplankton might be produced per year as a result of diffuser-induced upwelling. However, in this prediction no consideration was given to the interaction of the diffuser-induced upwelling with the San Clemente nearshore microfronts. Further, the biological and physical processes at San Onofre may be caused by this regional microscale frontal system. This study characterizes these regional microfronts in greater detail than previously reported (Grove and Sonu 1983).

To study the front more closely, we augmented satellite IR images with a low-altitude, helicopter-borne thermal infrared scanning system and with in situ profiling of water temperature from a surface vessel. We sought the following specific objectives:

1. To demonstrate the applicability of low-altitude thermal IR sensing for monitoring coastal fronts,
2. To identify the features associated with the coastal microfront in the vicinity of SONGS,
3. To assess the interaction of the microfronts with the nearshore waters near SONGS.

METHODS

Satellite thermal IR images were obtained for the survey days from the Scripps Institution of Oceanography Remote Sensing Facility.

The equipment for the low-altitude IR scanning consisted of a thermal imaging system (Flir Systems, Inc. model 1000B) mounted on a Hughes 500 helicopter. This IR scanning system is sensitive to temperature variations on the order of 0.2°C, but is reliable and easy to use. Its ability to instantaneously produce sea-surface temperature patterns on a video monitor aboard the helicopter permits coordination with a surface vessel for concurrent water temperature measurements.

The detector used in the thermal imaging sensor is mercury cadmium telluride, which has a spectral response range of 8 to 12 microns. The spectral peak of the detector at 10.6 microns is optimal for measuring sea-surface radiant emittance. The sensor is contained in a spherical case mounted in a remotely controlled gimbal fastened to the bottom of the helicopter. A video monitor and control panel is inside the helicopter.

The thermal imaging system provides a 17° (vertical) by 28° (horizontal) field of view. It displays a real-time video image of the temperature field by showing gray-scale levels on the video monitor corresponding to temperature bands.

After collecting the video IR images in the field, we chose several portions of the video tape for enhancement with a digital image enhancement system. We used the image processing system at the Remote Sensing Facility of Scripps Institution of Oceanography to digitally filter the video noise in the images and enhance the gray-scale contrast.

During the IR scanning flight, vertical temperature profiles were taken from a surface vessel along several transects, as directed by the observer in the helicopter. Ocean currents were measured by continuously recording current meters permanently moored near SONGS.

FIELD PROGRAM

A total of four low-altitude IR scanning flights were conducted: August 26, September 27, October 11, and October 12, 1983. Each flight was begun at approximately 0800 hours, because in the early morning there was minimal IR interference from solar and land reflection. We empirically determined that a satisfactory resolution of the thermal imaging system was retained at altitudes as high as 9,000 ft. Since this altitude also provided a large area coverage, we conducted the remaining flights as close to this altitude as permitted by weather conditions. The flights covered the area between Dana Point and a few miles south of SONGS, and as far as several miles offshore on a few occasions.

The prevailing environmental conditions during the IR flights are summarized in Tables 1 and 2. The wind data given in Table 1 are based on measurements made at SONGS meteorological station (SCE unpublished data). The ocean currents shown in Table 2 were measured near SONGS at four stations (Figure 1) and at two depths. The currents are given as hourly averages of the longshore component of the current between 0800 and 1300 hours.

DISCUSSION

The principle behind the IR scanner is that a sensor measures the amount of radiant flux emitted by a substance, in this case the ocean water, in the 8-to-12-micron wavelength band. Each substance emits radiant flux in proportion to its temperature, thus permitting a measurement of temperature by comparing the magnitude of the radiant flux. The radiant flux emitted from water is limited to the top few microns of the water surface in the 8-to-12-micron wavelengths; thus the temperatures measured are limited to the ocean surface. The radiant flux of a substance as measured by a remotely located IR sensor can be affected by several mechanisms such as atmospheric reflection and scattering of the emitted energy, absorption of the emitted energy by atmospheric moisture, and, in the case of a water surface, nonhomogeneous reflection

TABLE 1
Environmental Conditions during IR Overflights

Date	Weather	Flight altitudes	Concurrent satellite images	Ground truth	Comments
8/26 1983	Clear, winds from west @ 5-7 mph	5,000 ft. 9,000 ft.	NOAA-7, 8/25 NOAA-7, 8/28 NIMBUS-7, 8/26	None	Coastal front from Dana Point identifiable: strong front emanating from San Mateo Point
9/27 1983	Overcast at 5,000 ft., winds from north @ 8-10 mph	4,500 ft.	NOAA-7, 9/27	2 temperature transects	Thermal features in vicinity of San Mateo Point
10/11 1983	Clear, winds southwest @ 1-5 mph	5,000 ft. 9,000 ft.	NOAA-7, 10/12 NIMBUS-7, 10/12	4 temperature transects	Layered fronts near San Mateo Point; coastal front in vicinity of Dana Point
10/12 1983	Clear, winds from west @ 2-5 mph	5,000 ft. 9,000 ft.	NOAA-7, 10/12 NIMBUS-7, 10/12	4 temperature transects	Coastal front in vicinity of Dana Point

TABLE 2

Longshore Currents during IR Flights

Station UVT-1, 3-m depth

Time	8/26	9/27	10/11	10/12
8-9	—	−11.3	−5.1	2.0
9-10	—	−8.3	−5.3	2.3
10-11	—	−7.7	−5.0	3.9
11-12	—	−6.6	−5.2	2.3
12-13	—	−2.7	−6.1	0.8

Station UVT-1, 9-m depth

Time	8/26	9/27	10/11	10/12
8-9	−7.4	−4.8	−12.2	−7.5
9-10	−5.8	−7.8	−11.1	−4.7
10-11	−3.0	−6.9	−9.0	−4.7
11-12	−0.4	−6.5	−8.1	−5.4
12-13	—	−6.9	−4.6	−4.8

Station UVT-2, 3-m depth

Time	8/26	9/27	10/11	10/12
8-9	−31.4	5.2	−29.7	−27.3
9-10	−36.6	2.4	−27.2	−27.8
10-11	−37.3	−6.8	−26.4	−26.9
11-12	−34.5	−10.3	−26.3	−27.0
12-13	−27.7	−13.5	−26.9	−27.2

Station UVT-8, 3-m depth

Time	8/26	9/27	10/11	10/12
8-9	—	−6.8	−30.3	−26.2
9-10	—	−1.0	−32.0	−30.9
10-11	—	−1.8	−30.3	−31.8
11-12	—	−4.1	−32.8	−30.7
12-13	—	−8.9	−33.7	−32.3

Station UVT-8, 9-m depth

Time	8/26	9/27	10/11	10/12
8-9	−16.8	−7.0	−30.9	−21.5
9-10	−11.4	−4.9	−28.8	−24.4
10-11	−11.6	−6.9	−20.8	−17.9
11-12	−12.9	−6.0	−34.7	−16.5
12-13	−15.4	−3.9	−35.3	−20.8

Station UVT-9, 3-m depth

Time	8/26	9/27	10/11	10/12
8-9	−14.1	—	—	−23.0
9-10	−15.0	—	—	−31.1
10-11	−11.2	—	—	−34.6
11-12	−7.9	—	−45.9	−35.0
12-13	−4.5	—	−31.6	−36.7

Station UVT-9 9-m depth

Time	8/26	9/27	10/11	10/12
8-9	−2.4	−10.3	−9.8	−26.0
9-10	1.0	−12.1	−16.1	−21.9
10-11	1.7	−13.1	—	−19.0
11-12	3.7	−16.4	−24.7	−23.8
12-13	7.4	−11.9	−31.7	−23.1

Note: Negative longshore currents are downcoast (i.e., 130 deg true). Current speeds are expressed in cm/sec.

of ambient radiance caused by surface waves. Despite these sources of interference, IR scanning has proved useful for qualitatively describing ocean surface temperature differences.

The IR images from the helicopter are shown as oblique images taken toward the northwest. The shoreline in all cases is shown along the right edge of the photos; the land is black. Warmer ocean temperatures are shown as darker shades of gray; cooler ocean temperatures are lighter shades of gray.

Front at Dana Point

During the IR scanning flight of August 26, 1983, we observed a front extending southeast from Dana Point (Figure 2). The image shows Dana Point in the upper right corner, with a cool water mass (lighter shades) extending toward the bottom of the photo. On this particular occasion, the front appeared as the offshore edge of a large cool-water plume extending from its point of origin. The plume then formed a narrow band of cool water surrounded by warm water both on its onshore and offshore sides as it streamed downcoast. Review of data indicates the existence of a southeastward flow at all the current-meter stations. The hourly average longshore current component reached as high as 37.3 cm/sec at the farthest offshore station, station UVT-2, at a depth of 3 m.

A satellite thermal IR image, taken August 25 at 1503 hours, confirms the existence of the front emanating southeast from Dana Point. This satellite image, shown in Figure 3, does not contain the resolution necessary to identify the separation of the front from the shoreline as observed in the low-altitude image (Figure 2). However, it does show the existence of another front farther offshore. The cool-water tongue offshore is the result of a cool-water plume emanating from Palos Verdes, farther north. A second front at the edge of this plume was observed from the helicopter with the IR scanner, but the front was too extensive to adequately map.

During the IR scanning flight of September 27, 1983, we found no front emanating south or southeastward from Dana Point. A satellite thermal IR image taken at 1502 hours on September 27 confirmed these results. The satellite image, shown in Figure 4, indicates a coastal front to the northwest of Dana Point but not to the southeast. Current-meter data indicate that the southeastward flow was weaker than during the

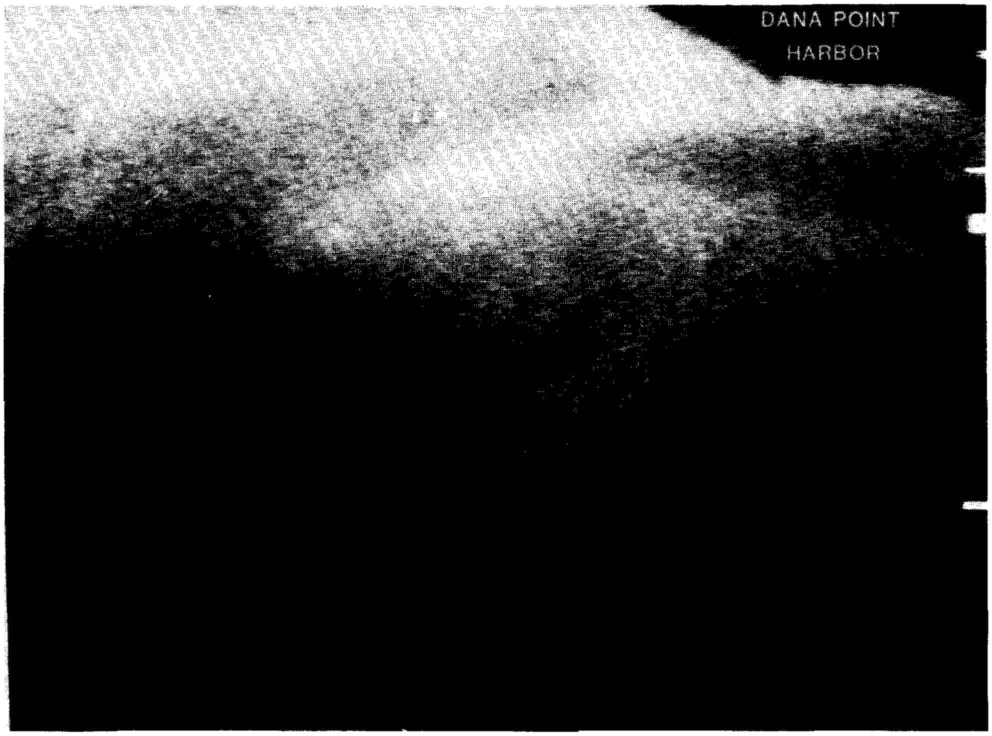

Figure 2. Front extending to the southeast from Dana Point, August 26, 1983 (Dana Point shown on black area in upper right corner).

other flights, and in the case of station UVT-2, the farthest offshore station, the data indicate a current towards the northwest as high as 5.2 cm/sec between 0800 and 0900 hours.

A coastal front emanating from Dana Point toward the southeast was again observed on October 11 and 12. A sample IR image in the vicinity of Dana Point is shown in Figure 5. This IR image was taken from an altitude of 9,000 ft. Dana Point and Dana Point Harbor can be seen as the black area in the upper right corner of the photo. To the southeast of Dana Point there is a very definite cool-water mass, which is attached to the shoreline in this particular case. It is obvious that the cool surface water originates at Dana Point. Hourly average currents on this particular date were on the order of 30 cm/sec to the southeast at the

Figure 3. NOAA-7 satellite IR image of August 25, 1983, indicating existence of coastal front to southeast of Dana Point.

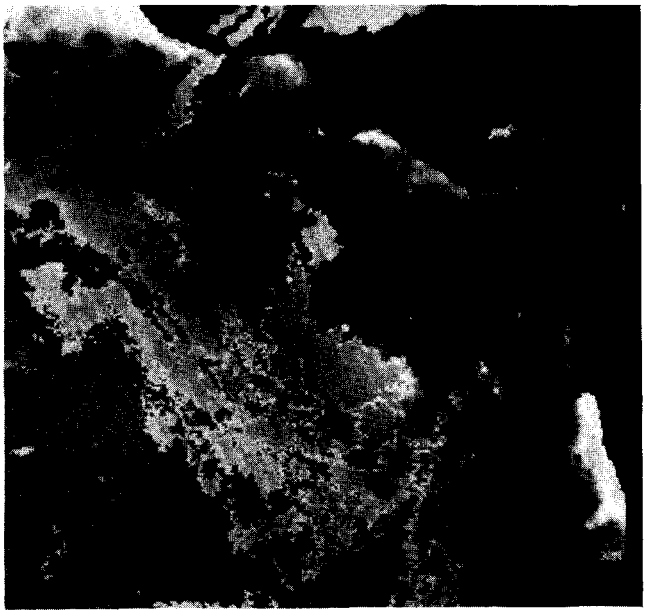

Figure 4. NOAA-7 satellite IR image of September 27, 1983, indicating the lack of a coastal front during the low-altitude IR overflight of the same date.

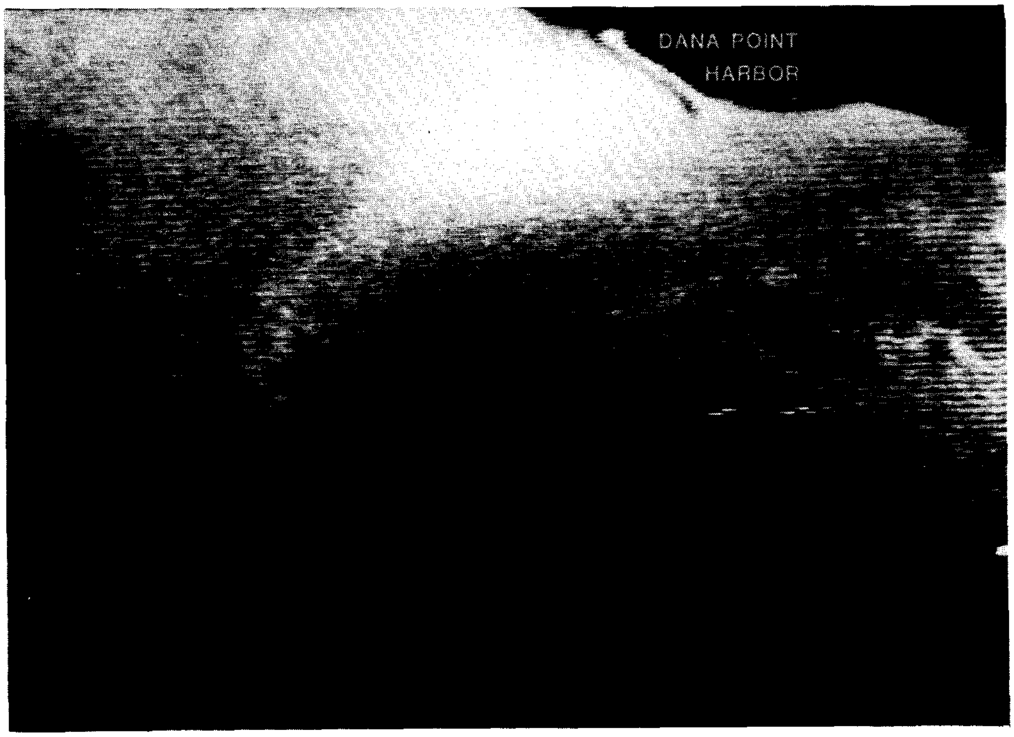

Figure 5. Oblique low-altitude IR image of coastal front emanating from Dana Point on October 12, 1983.

offshore stations at a depth of 3 m. The inshore currents, measured at station UVT-1, were actually toward the northwest at this depth, indicating the possible presence of an eddy.

The likely mechanism contributing to the upwelling in the lee of Dana Point is a cyclonic (counterclockwise) gyre, which develops at this location under a persistent northwesterly wind (Grove and Sonu 1983). Because of the cyclonic motion, the thermocline will be raised toward the surface at the center of the gyre, serving as a stationary source of cold water (Defant 1961). The cold water, upon reaching the surface, is then advected in the mean southward current, extending its plume along the downcoast shoreline. A schematic illustration of the mechanisms responsible for the front is shown in Figure 6. The mechanisms illustrated include both the conventional interpretation of upwelling as local Ekman transport offshore, and the upwelling induced by the cyclonic gyre in the lee of the headland. It is readily apparent that these two mechanisms are not exclusive but rather that they reinforce each other.

During the IR scanning flight of October 12, we visually confirmed the existence of the cyclonic gyre at Dana Point. The gyre, observed as a series of spiralling surface slicks, was estimated to be on the order of 1 km in diameter. There are also several photos of the San Mateo Point region dating back to January 22, 1973, that document a distinct turbidity pattern in the form of a cyclonic gyre with a diameter of 1 to 4 km separating from the point (Wheeler North, pers. comm.).

Front at San Mateo Point

The front originating at San Mateo Point varied markedly from flight to flight, more so than the one at Dana Point. Two scenes of the front at this location

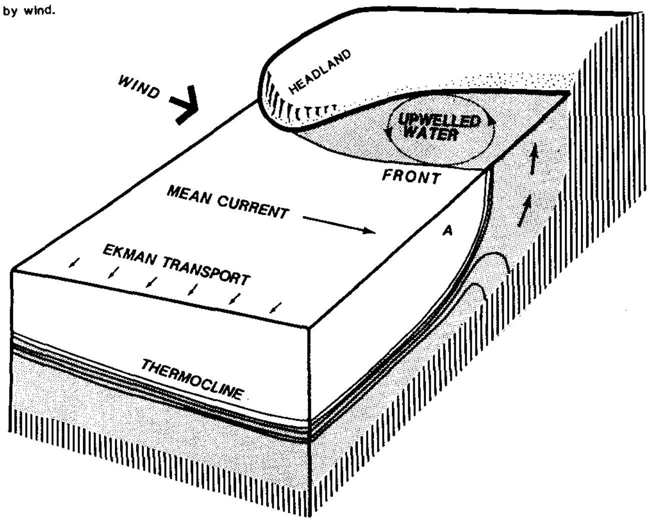
The upwelled water adjacent to the shoreline is the result of a raised thermocline at the center of a cyclonic gyre in the lee of the headland combined with offshore Ekman transport induced by wind.

Figure 6. Schematic of the front formation in the lee of a headland.

Figure 7. Oblique low-altitude IR image of front at San Mateo Point September 27, 1983.

are shown in Figure 7 (September 27) and Figure 8 (October 11).

The IR image of September 27 shown in Figure 7 reveals a cool-water plume intersecting the San Mateo Point shoreline at a large angle and extending offshore. The shape of the front on this date, coupled with a northerly displacement of the front as compared with other dates, suggests that a northward-flowing current has deflected a previously coast-parallel front to become a shore-perpendicular front. Current-meter data indicate that the offshore currents (station UVT-2) were toward the northwest at the 3-m depth, but the remaining stations and depths all indicate a flow to the southeast. It is likely that currents at San Mateo Point are most closely represented by the currents at station UVT-2. The fact that the 60-ft isobath approaches the shore at San Mateo Point from SONGS (Figure 1) reinforces this conclusion. The coastal currents would tend to follow the bathymetry and thus approach San Mateo Point.

During the IR scanning flight of October 11, we observed a multilayered front in the vicinity of San Mateo Point (Figure 8). This IR image reveals a very clear front adjacent to shore, a front shown as a streak farther offshore, and a third front, barely visible, even farther offshore. A possible linkage on this date between thermal fronts and turbidity fronts at this location is suggested by observations of turbidity coinciding with the thermal fronts.

Two temperature contour plots derived from the ground truth temperature survey taken from the surface vessel on October 11 are shown in Figures 9 and 10. The temperature transect illustrated in Figure 9 was taken nearly normal to the shoreline, upcoast of San Mateo Point; the temperature transect shown in Figure 10 was taken normal to the shoreline just downcoast of San Mateo Point.

These temperature contour plots indicate a well-mixed layer in the top 5 m of the water column, with a thermal stratification between the bottom and 5-m-depth of as much as 2°C on both the upcoast and downcoast side of San Mateo Point. The noticeable slanting of the isotherms upward toward shore on the downcoast transect (Figure 10) may indicate a source of upwelling at this location or possibly a geostrophically balanced downcoast flow. The surface temperatures along the transect decrease as much as 1°C between the offshore and onshore limits of the transects. Both temperature contour plots confirm the existence of the front at San Mateo Point and suggest that the temperature difference across the front is on the order of 1°C.

CONCLUSIONS

The helicopter-borne thermal IR scanner proved quite useful in resolving oceanographic surface features such as coastal fronts. The system's advantages are that it has high resolution and is compact, reliable, and easy to operate, qualifying it as a valuable tool for thermal surveillance operations in the coastal area. A

Figure 8. IR image of a multilayered front adjacent to San Mateo Point October 11, 1983 (photo taken toward northwest).

principal constraint is the system's relatively small field of view, which makes it necessary to operate the equipment at a high altitude or to aim obliquely. Although a computerized rectification procedure can be used to geographically register the video images, filter the noise, and enhance the image quality, the extra processing is of limited usefulness.

Whereas the coastal front as viewed on satellite imagery had remained somewhat blurred because of the 1.1-km spatial resolution, the low-altitude thermal IR scanning plus ground truth measurements as reported in this paper have reinforced the concept of the microfront at this location. The front forming at Dana Point did actually peel off the sharp bend of the coast at the point, suggesting a mechanism similar to the detachment of a boundary layer at a sharp corner. A cyclonic gyre, the source of the Dana Point coastal front that had been hypothesized in the past, was seen during this study.

The coastal front forming at Dana Point, observed by the thermal IR scanner on three out of four survey days, extended southward beyond San Mateo Point and SONGS. This observation was supported by the satellite images from these days. On the fourth day the satellite image showed possible upwelling and frontal activity displaced to the north side of Dana Point, an area not covered by the helicopter IR survey.

An unexpected discovery of an additional distinct, more localized frontal system at San Mateo Point is an important result of this study. This particular microfront, not evident in satellite images, seemed to intersect the coastline at larger angles than the front at Dana Point, although its configuration appeared to depend heavily on the local current system.

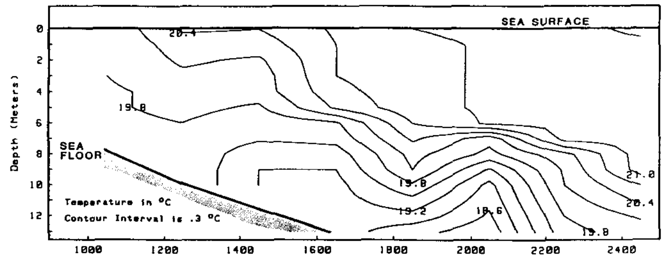

Figure 9. Temperature contours upcoast of San Mateo Point, October 11, 1983.

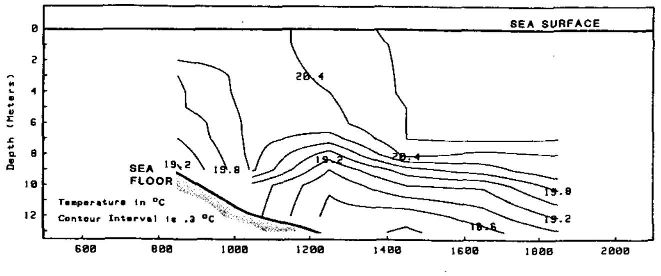

Figure 10. Temperature contours downcoast of San Mateo Point, October 11, 1983.

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