NASA TM-86712

NASA Technical Memorandum 86712

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N85-35573#

SEA SURFACE AND REMOTELY SENSED TEMPERATURES OFF CAPE MENDOCINO, CALIFORNIA

Laurence C. Breaker,* John C. Arvesen, David Frydenlund (LCDR),†
Jeffrey S. Myers,‡ and Kent Short§

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SUMMARY

During September 3-5, 1979, a multisensor oceanographic experiment was conducted off Cape Mendocino, California. The purpose of this experiment was to validate the use of remote sensing techniques over an area along the U.S. west coast where coastal upwelling is known to be intense. Remotely sensed multispectral data, including thermal infrared imagery, were collected above an upwelling feature off Cape Mendocino. Data were acquired from the TIROS-N and NOAA-6 polar orbiting satellites, the NASA Ames Research Center's high altitude U-2 aircraft, and a U.S. Coast Guard C-130 aircraft. Supporting surface truth data over the same feature were collected aboard the National Oceanic and Atmospheric Administration (NOAA) ship, OCEANOGRAPHER. Atmospheric soundings were also taken aboard ship.

The results indicate that shipboard measurements of sea surface temperatures can be reproduced within 1°C or better through remote observation of absolute infrared radiance values (whether measured aboard the NOAA polar orbiting satellite, the U-2 aircraft, or the Coast Guard aircraft) by using appropriate atmospheric corrections. Also, the patterns of sea surface temperature which were derived independently from the various remote platforms provided a consistent interpretation of the surface temperature field.

INTRODUCTION

High resolution infrared satellite coverage along the U.S. west coast first became available on an operational basis to the civilian community in 1974. The Very High Resolution Radiometer (VHRR) aboard the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellite NOAA-3 provided infrared data for a new and detailed view of surface thermal patterns along the west coast. However, the time and space scales associated with the patterns, apparently often related to coastal upwelling, conflicted somewhat with traditional views of circulation in the California Current. For example, filaments of cold upwelled water were often seen extending several hundred kilometers from the coast, well beyond the expected range of coastal upwelling. It was not known whether these features were primarily surface phenomena or whether they might extend well below the surface. The need for

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supporting surface truth data became apparent in order to provide a basis for interpreting this new source of information.

During the period that preceded the experiment described herein (1975-1979), very little surface truth data had been collected along the west coast in support of infrared satellite coverage. However, infrared data from Coast Guard aircraft using an Airborne Radiation Thermometer (ART) were collected along the west coast out to about 200km on a regular basis since 1963 (ref. 1). Spatial and temporal coverage were, by necessity, limited because of the platform used. Surface truth data has been compared with the high resolution infrared data from the NOAA-3, -4,-5 satellites in the eastern tropical and subtropical Pacific in a series of reports by the Inter-American Tropical Tuna Commission (refs. 2, 3, and 4). Unfortunately, these comparisons were concentrated mainly in the Gulf of California, an area whose oceanic characteristics differ from those along the U.S. west coast. Similar comparisons have also been made by Tabata and Gower (ref. 5) off the coast of Vancouver Island on several occasions, and sea surface temperatures measured aboard ship were found to be highly correlated with calibrated infrared satellite measurements over the same area. However, these results are limited mainly to an offshore area north of 48°N where coastal upwelling is not intense. Also, these results do not explicitly take into account atmospheric effects because sounding data were apparently not available.

Data from both the VHRR aboard a NOAA polar-orbiting satellite and a Defense Meteorological Satellite Program (DMSP) satellite were compared with surface truth data collected off central and southern California, respectively (ref. 6). Off Pt. Conception, surface indications of a warm intrusion were found to extend 300m below the surface. Off southern California, generally close agreement was found between sea surface temperatures derived from the military DMSP satellite and temperature fields constructed from aircraft Airborne Expendable Bathythermograph data at the surface and at a depth of 200m. These sets of surface truth data constitute the only known data collected in the general area of interest up to the time of this experiment.

One of the most interesting revelations from high resolution infrared satellite coverage along the U.S. west coast has been the regular occurrence of elongated filaments of upwelled water that may extend several hundred kilometers off the coast. These filaments are found particularly along the California coast from Pt. Conception to Cape Mendocino from about April to October. As a result, Cape Mendocino was chosen as the site for a surface truth experiment to examine upwelling both remotely and from aboard ship.

The NOAA ship, OCEANOGRAPHER, was available for a 2-day period to collect data within the Cape Mendocino study area during a return trip to Seattle, Washington. The U.S. Navy at the North Island Weather Facility in San Diego took atmospheric soundings aboard ship during the experiment. NASA Ames Research Center utilized a high altitude U-2 aircraft to collect multispectral imagery off the coast to a distance of 105 km, and the U.S. Coast Guard participated by collecting ART data from a C-130 aircraft flying over the area.

Individuals, or groups, representing four government agencies were represented: Department of Transportation, NASA, Navy, and NOAA (within NOAA: the National Earth Satellite Service, the National Ocean Survey, the NOAA Corps, and Sea Grant). Additionally, the Scripps Institution of Oceanography and a California State University

Laboratory (Moss Landing Marine Laboratory) participated in the overall data collection effort.

The body of this report is divided into five sections. The first section describes the setting and conduct of the experiment. The second section contains the satellite data and associated results. The third section contains the U-2 multispectral scanner results. The fourth section includes the Coast Guard ART results, and the final section compares the various results and presents various conclusions resulting from the study.

I. SETTING AND CONDUCT OF THE EXPERIMENT

Cape Mendocino is a major turning point along the west coast of the United States. It is located at about 40.3°N, 124.4°W. This Cape is actually composed of two smaller Capes, Cape Mendocino to the north and Punta Gorda to the south. These two Capes are located about 20 km apart and the atmospheric and oceanic coastal circulation patterns are altered by their presence. In the mean, both the winds and the currents tend to follow the changing coastline in this region.

During September, prevailing surface winds are from the NNW at approximately 8 m/sec (ref. 7). Because of coastal upwelling, sea surface temperatures are generally slightly lower than air temperatures, resulting in a marginally stable marine boundary layer.

Sea surface temperatures in the vicinity of Cape Mendocino average about 14°C during September (ref. 8). However, satellite imagery has shown repeatedly that the surface temperature distribution near Cape Mendocino is complex because of frequent upwelling at this location. Long filaments of upwelled water are often seen extending several hundred kilometers off Cape Mendocino and directed generally to the southwest. The depth of the mixed surface layer may be less than 15 m at this time of year. Surface salinities range between 32.7 and 33.1 PPT and may increase slightly near the coast because of the upwelling of subsurface water of higher salinity. Instantaneous surface flow in the area is expected to be highly variable in speed and direction due to the effects of local upwelling.

The bottom topography off Cape Mendocino is dominated by the presence of the Mendocino Ridge which extends almost due west off the Cape itself. Within about 125 km of the coast, bottom topography is dominated by the Gorda Escarpment and the Mendocino and Mattole submarine canyons.

During September 3 and 4, 1979, winds recorded aboard ship were usually weak and variable in direction. For a brief period on September 4, winds approached 8 m/sec. Usually, however, wind speeds were 5 m/sec or less. Wind conditions observed aboard ship were consistent with the predicted synoptic scale surface winds for this area during the period of the experiment and for about 2 weeks prior to the experiment. Figure 1 shows wind stress magnitude calculated from the observed pressure field for a location centered at 39°N and 125°W. During the two-week period prior to the experiment, wind stress exceeded 1 dyne/cm^2 less than 10% of the time. The upwelling index, which is also shown in figure 1, is directly proportional to the wind stress. This index predicts the associated offshore Ekman transport normal to the coast, which is an indicator of upwelling intensity expected at this location. Upwelling indices during and prior to the experiment were consistently lower than values usually expected for this area and, as a result, intense upwelling was not expected.

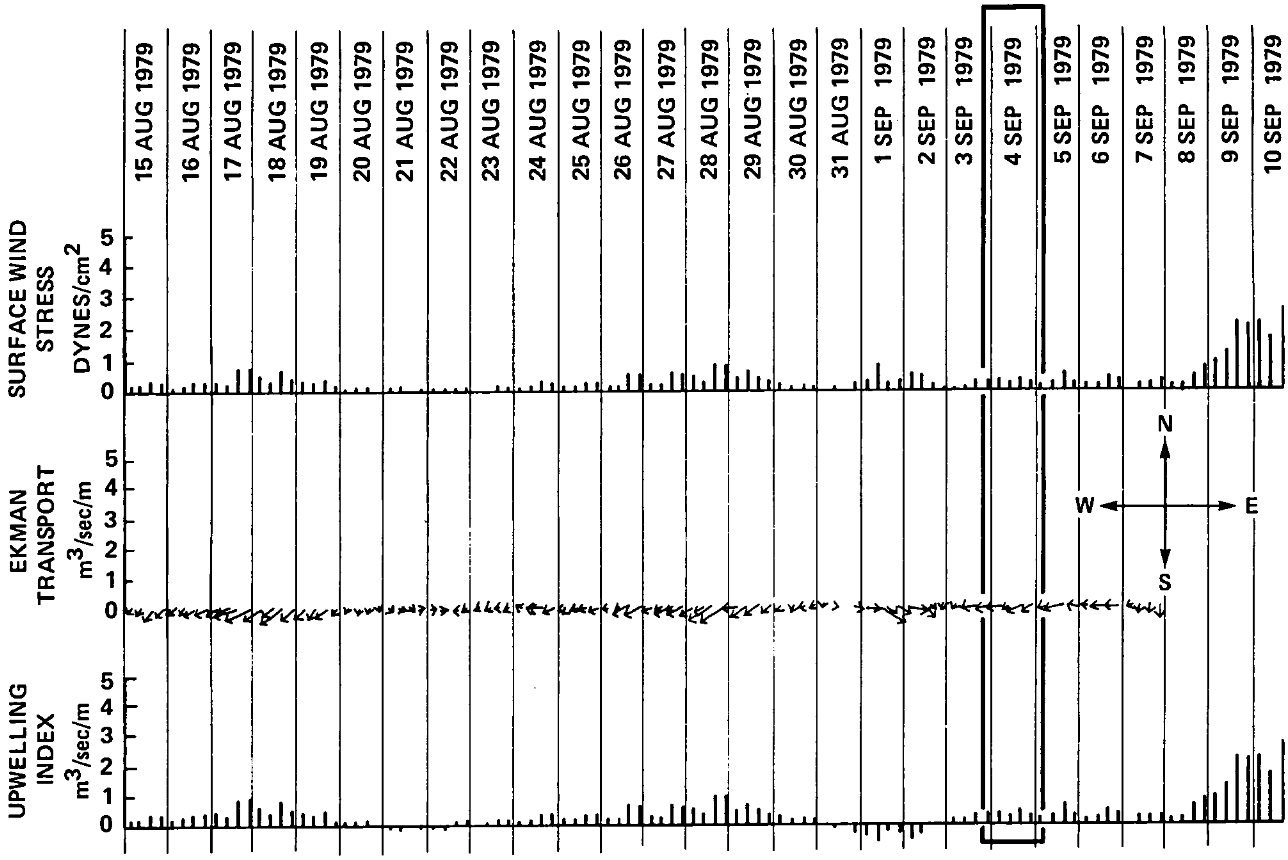


Figure 1.- Time series of wind stress magnitude, offshore Ekman transport, and upwelling index at 39°N, 125°W.

The plan of the experiment was to collect oceanographic data over a flexible grid at regularly spaced intervals, bearing in mind that grid changes might be indicated from satellite coverage of the area just prior to, and during, the experiment. It was intended that the satellite data be used to guide the ship to an area near Cape Mendocino where, with a little luck, a suitable feature would be found. Such a feature was found on September 3, 1979, and its presence was reaffirmed on three subsequent satellite passes. The location of this feature was relayed to the ship via radiotelephone and radio facsimile. Thus, it was possible to provide real-time guidance for optimum shipboard coverage of the feature. The ship's track as actually executed is shown in figure 2 overlaid on the map of the study area. Shipboard measurements included Expendable Bathythermograph temperature profiles, salinity/temperature/depth profiles, and continuous records of sea-surface temperature from the ship's intake thermometer and a Barnes Engineering PRT-5 radiometer. Bucket temperatures were also taken at selected locations along the track. Finally, nine radiosonde balloons were launched during the experiment which provided atmospheric profiles of temperature and humidity.

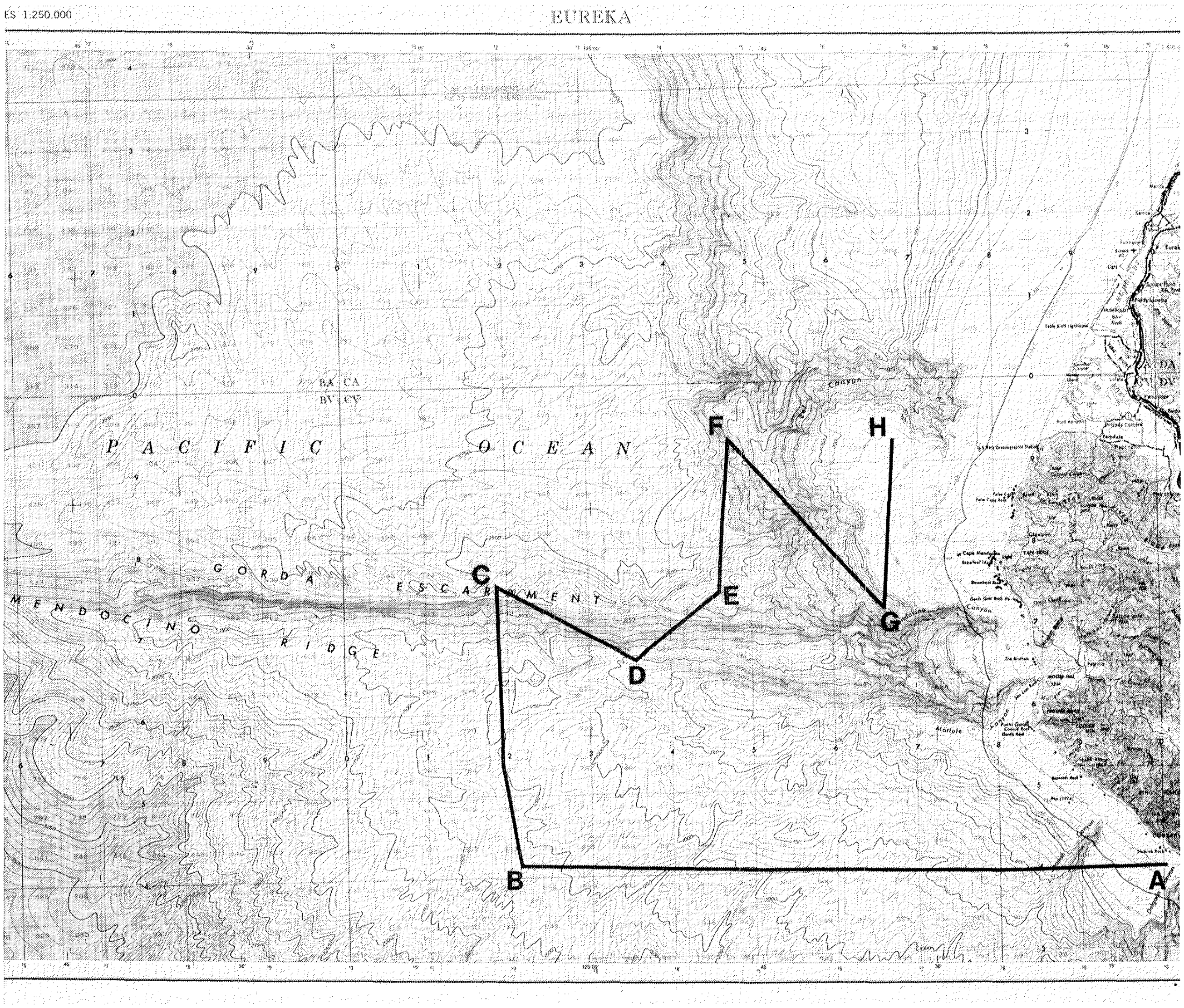


Figure 2.- Track map of NOAA Ship OCEANOGRAPHER, from 0736 Greenwich Mean Time GMT, September 3 (A) to 0944 GMT, September 5, 1979 (H).

During midday September 4, 1979, the Coast Guard C-130 aircraft made ART measurements along the flightlines shown in figure 3. The NASA U-2 aircraft collected multispectral scanner imagery within the study area shown in figure 4 at the same time that the OCEANOGRAPHER and the Coast Guard aircraft were in the area.

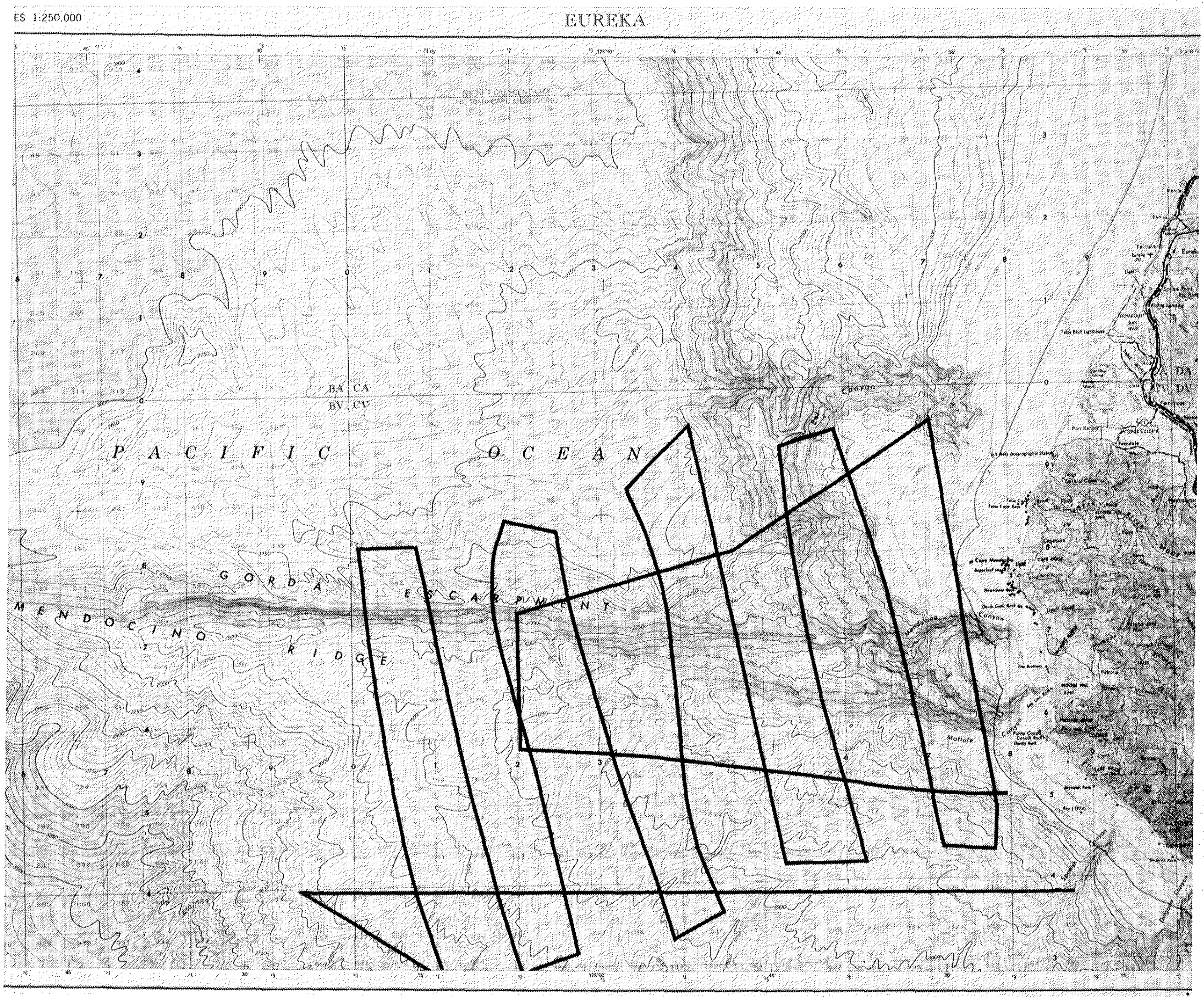


Figure 3.- Track/map of U.S. Coast Guard C-130 ART measurements September 4, 1979.

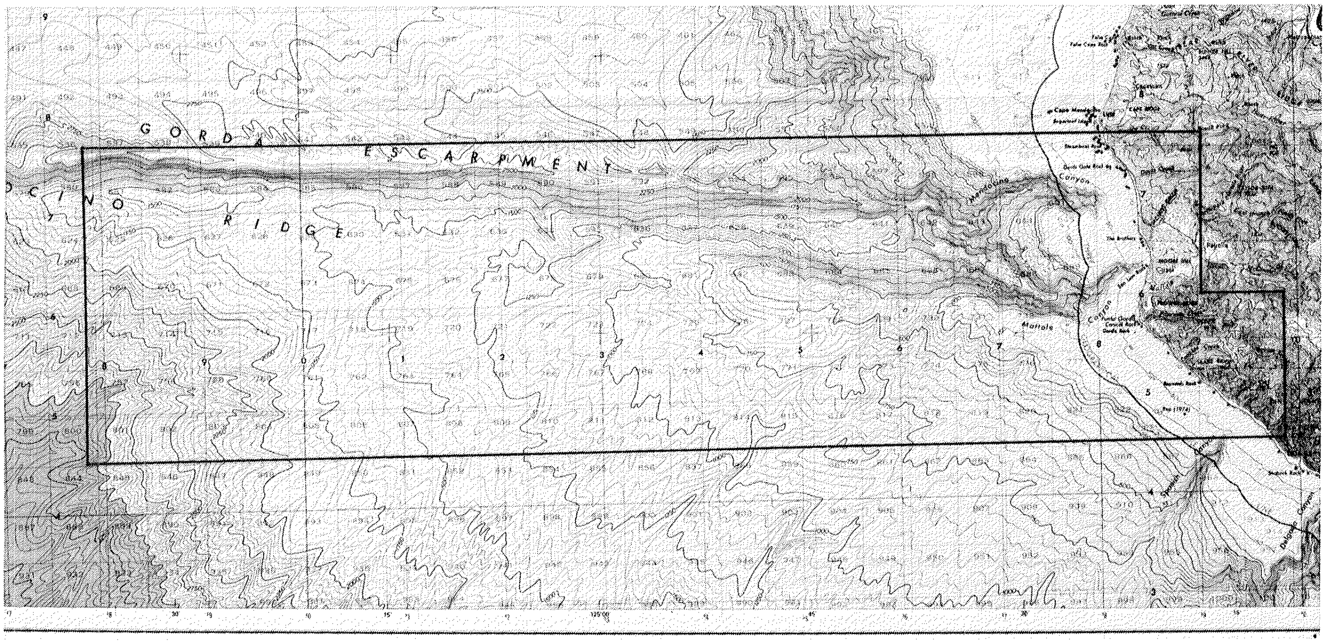


Figure 4.- Study area imaged by multispectral scanner aboard NASA U-2 aircraft from 1917 to 1944 GMT, September 4, 1979.

II. SATELLITE COVERAGE FROM THE TIROS-N AND NOAA-6 POLAR ORBITING SATELLITES

TIROS-N and NOAA-6 were the first two satellites in the TIROS-N series of third generation NOAA polar-orbiting satellites. The TIROS-N satellite system was designated to be a two-satellite system with nominal altitudes of 833 and 870 km. The orbits are sun-synchronous and have a nodal period of about 1 hour and 42 minutes (ref. 9). Cross-track coverage over the ground is about 6200 km. Two overhead passes per day are received from each satellite with roughly 6 hours between successive passes.

The TIROS-N satellite data presented here was received and processed at Redwood City, California. The particular sensor from which this information was acquired was the Advanced Very High Resolution Radiometer (AVHRR). The AVHRR is a five-channel scanning radiometer sensing both reflected and emitted radiation in the visual and infrared portions of the electromagnetic spectrum, respectively. The spectral characteristics of the TIROS-N and NOAA-6 instruments are shown in the following table:

TABLE 1.- SPECTRAL CHARACTERISTICS OF THE AVHRR

TIROS-N		NOAA-6	
Channel number	Spectral band (μm)	Channel number	Spectral band (μm)
1	0.55 - 0.90	1	0.55 - 0.68
2	.725 - 1.10	2	.725 - 1.10
3	3.55 - 3.93	3	3.55 - 3.93
4	10.5 - 11.5	4	10.5 - 11.5
5	Channel 4 data repeated	5	Channel 4 data repeated

The spatial resolution of the AVHRR is 1.1 km directly below the spacecraft, becoming lower as the scan departs from nadir. The noise equivalent differential temperature (NEΔT) of the AVHRR is less than 0.12°C, the least-count resolution of the 10-bit data received directly from the spacecraft (ref. 9).

Three overhead passes were received from TIROS-N and one from NOAA-6 during the 24-hour experiment. The corresponding images depict the upwelling feature at various times (figs. 5 through 8). These images have been digitally enhanced to increase the contrast in grey levels. The images have also been geometrically corrected for satellite viewing angle and earth curvature. However, they have not been corrected for the effects of earth rotation.

The images portray an upwelling feature originating at the coast and extending about 150 km. A few high clouds obscure small portions of the feature in figures 5, 6 and 7. In figure 8, what may be an aircraft contrail is seen extending to the northwest away from the northern edge of the feature. The coldest water is seen near the coast between Cape Mendocino and Point Delgada (fig. 8). The apparent upwelling source region expands offshore roughly in the area between Cape Mendocino and Pt. Arena, approximately 150 km to the south. The axis of the feature more or less parallels the Gorda Escarpment.

The sequence of images indicated slight movement of the feature over the 24-hour period. This movement was detected by transferring the boundaries associated with the feature from the four images to a base map as shown in figure 9. Arrows have been drawn to indicate the net motions inferred. Part of the apparent motion, however, may be due to geometrical distortions still contained in the data.

Ten-bit digital AVHRR data were obtained for NOAA-6, orbit number 986, from the Scripps Remote Sensing Facility, Scripps Institution of Oceanography. The image shown in figure 10 was produced from this 10-bit data for the visual part of the spectrum (0.55-0.68 μm). This image showed a noticeable increase in surface reflectance near Cape Mendocino. The highest reflectance occurs immediately adjacent to Cape Mendocino with reflectance decreasing away from the coast. The increase in reflectance may be due to sediment flowing south from the Columbia River and becoming entrained in the offshore circulation associated with the Cape Mendocino upwelling feature. This interpretation, although tentative, is based on observations from the OCEANOGRAPHER of lower salinities in this area and the supposition that the volume of local river discharge near Cape Mendocino is far too small to produce any detectable change in reflectance at this time of year.

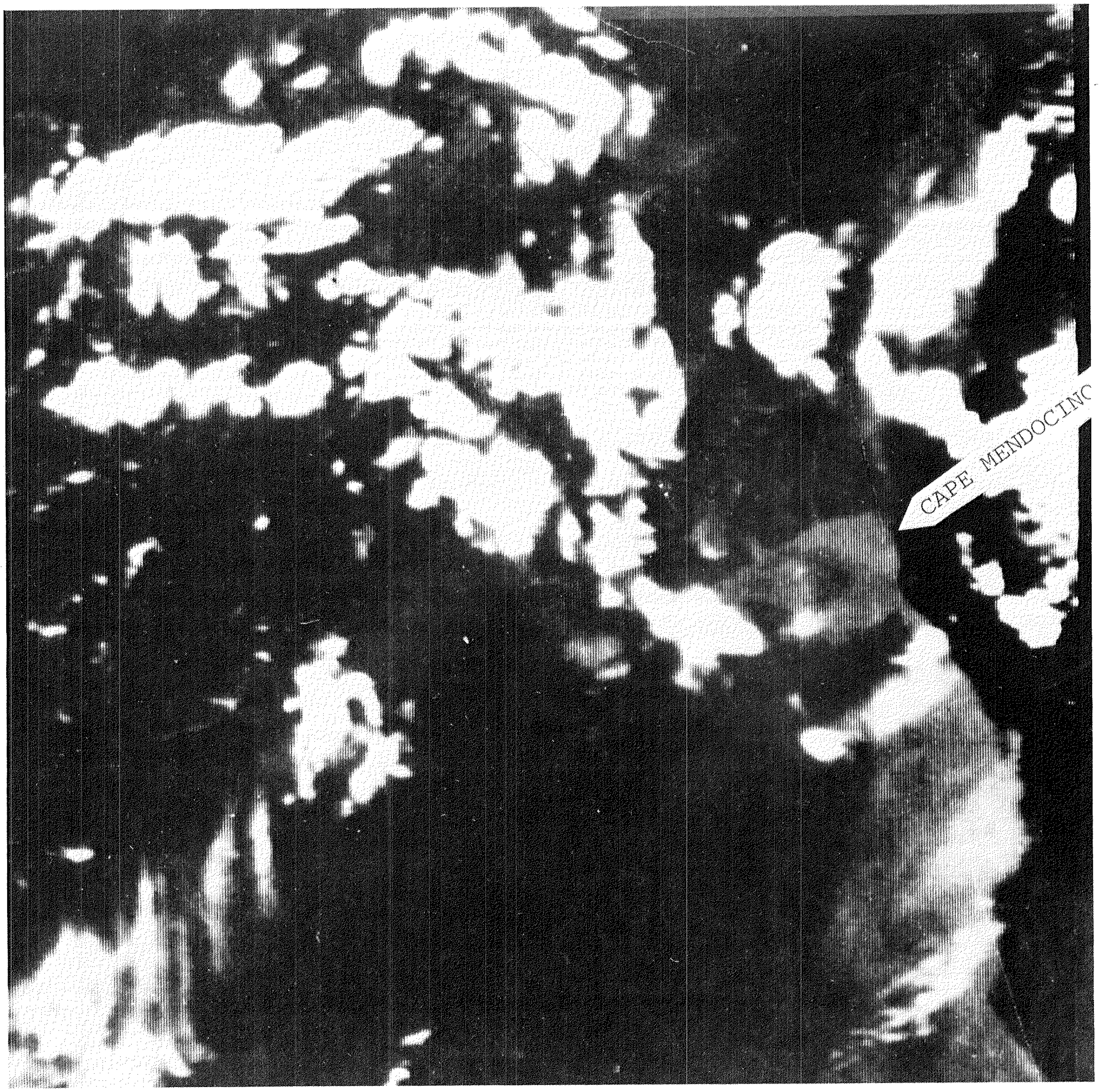


Figure 5.- TIROS-N Orbit 4591; September 3, 1979, 2340 GMT (11 µm).

Figure 6.- TIROS-N Orbit 4598; September 4, 1979, 1204 GMT (11 µm).

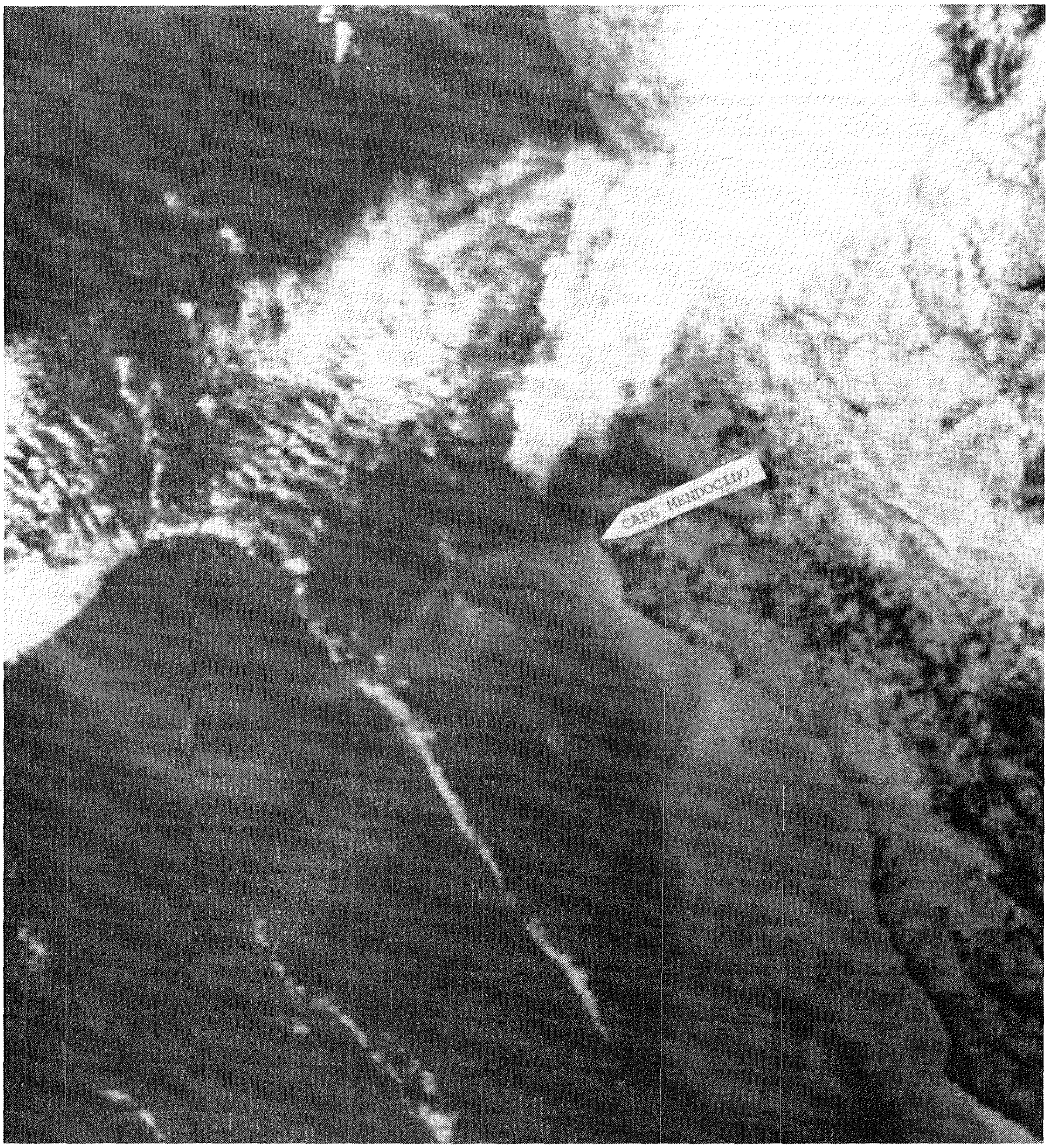


Figure 7.- NOAA 6 Orbit 981; September 4, 1979, 1624 GMT (11 μm).

Figure 8.- TIROS-N Orbit 4605; September 4, 1979, 2330 GMT (11 μm).

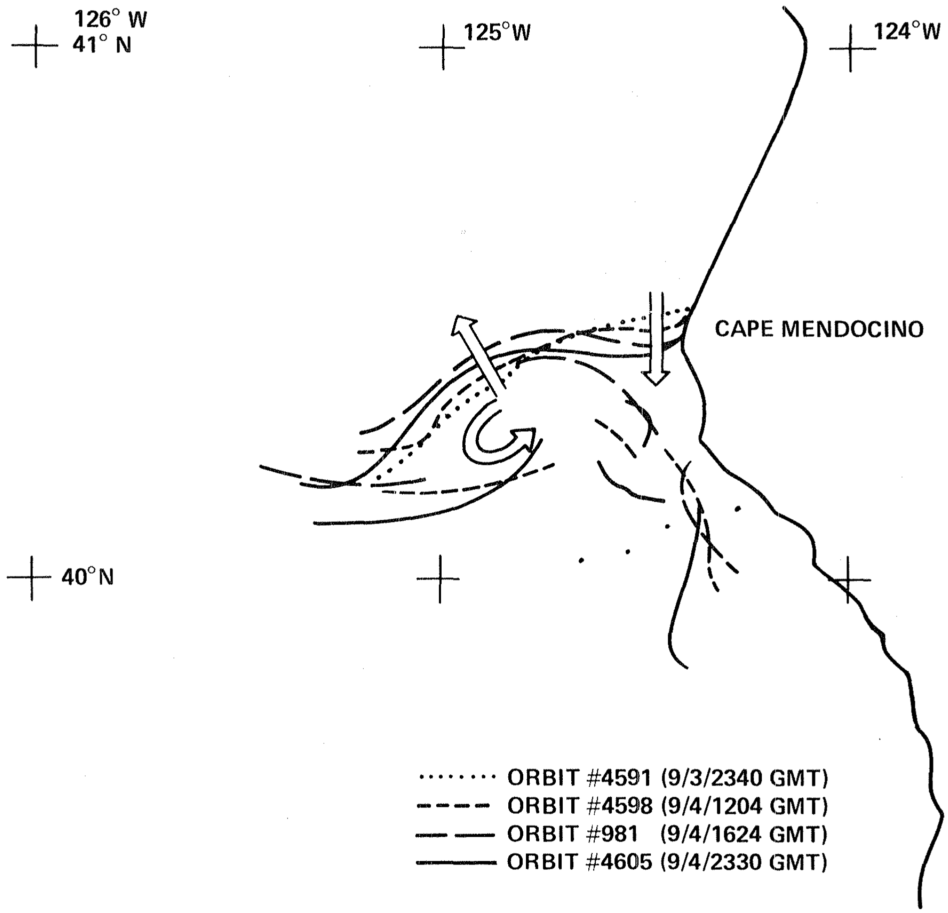


Figure 9.- Four image composites of IR thermal boundaries associated with the Cape Mendocino upwelling feature. Sequence covers approximately 24 hr.

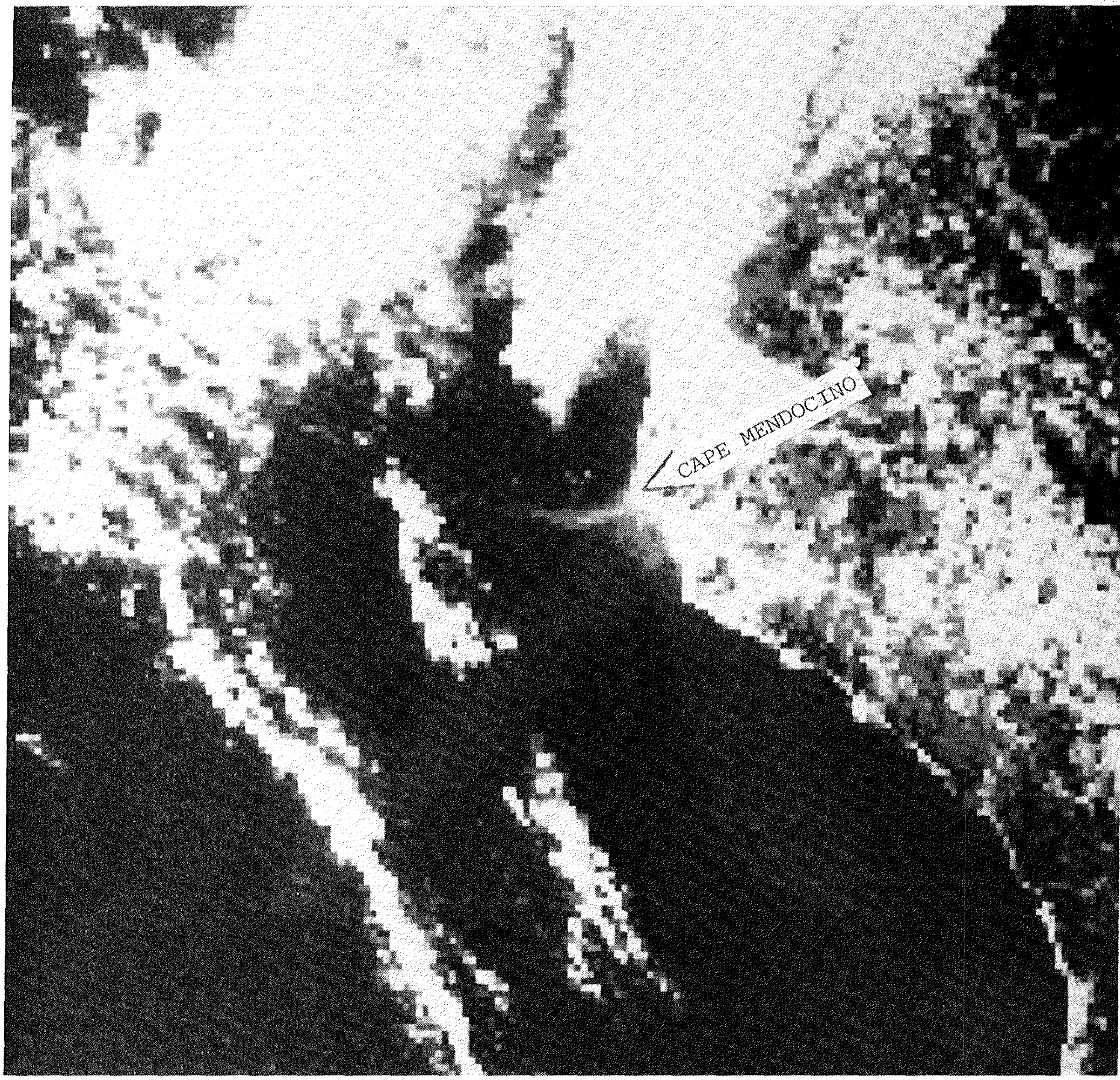


Figure 10.- NOAA-6 Orbit 981; September 4, 1979, 1624 GMT (VISUAL: 0.55-0.68 μm) 10-bit data.

Analysis of the infrared 10-bit digital data is deferred until section V, where it is compared with shipboard data.

III. MULTISPECTRAL OBSERVATIONS FROM THE NASA U-2 AIRCRAFT

Since 1971 NASA has operated two high altitude U-2 aircraft for remote sensing and air sampling purposes. A wide variety of photographic and electronic instrumentation has been integrated into these aircraft and utilized for many applications.

The U-2 aircraft operates at 21 km altitude, above approximately 95% of the atmospheric air mass and virtually all of the water vapor and particulates. Thus, Earth radiance measurements made from the U-2 aircraft closely approximate similar measurements from a satellite.

The instrument flown aboard the U-2 for the present study was a Daedalus Enterprises, Inc. DEI-1260 Multispectral Scanner. This scanner is located within an equipment bay on the U-2 aircraft and views the Earth through an opening in the lower hatch. Eleven detectors are located at the focus of a Newtonian telescope whose field of view is scanned perpendicular to the flight path by a rotating mirror. The scanner has ten channels in the visible/near-infrared spectral region and one channel in the thermal infrared (10.5-12.5 μm). Each scanline is digitized to produce 715 pixels at 8-bit resolution and recorded on magnetic tape. The scanner has a swath width of 16 km and a resolution of 25 m from an altitude of 21 km.

The sensitivity of the thermal channel is 0.3°C with an absolute radiometric accuracy of approximately ±0.5°C. The thermal channel is continuously calibrated by referencing each scan to two thermally controlled surfaces. The imagery is computer processed to produce calibrated black and white photographs with radiometric temperatures expressed as grey level values.

Two flightlines were flown to 105 km directly due west of Cape Mendocino during the period 1917 to 1944 Greenwich Mean Time (GMT) on September 4. Flightline selection was based on earlier satellite observations of the selected upwelling feature. A mosaic of the resulting thermal imagery is shown in figure 11. Because of the higher spatial resolution, more detailed structure is seen in the airborne imagery, but the general upwelling pattern is similar to the one shown in the previous satellite imagery.

Discrete temperature values from the thermal data were selected at locations along the path of the OCEANOGRAPHER. These data were corrected for atmospheric effects by using the LOWTRAN 4 radiative transfer model (ref. 11) and are compared with observations from satellite and shipboard in section V. The NOAA ship OCEANOGRAPHER was imaged at 1942 GMT on its due north track across the feature.

The inshore region of the northernmost flightline was analyzed in the blue (0.42-0.45 μm), green (0.50-0.55 μm) and red (0.65-0.69 μm) spectral regions to obtain a qualitative evaluation of suspended sediment and chlorophyll-like pigments in the upper water layers. The resultant imagery is shown in figure 12. The red image shows relatively bright near-shore features, attributed to high sediment levels, similar to observations apparent in the NOAA-6 imagery discussed previously. The blue/green ratio shows lower values near shore, possibly indicative of relatively higher chlorophyll content in these waters.

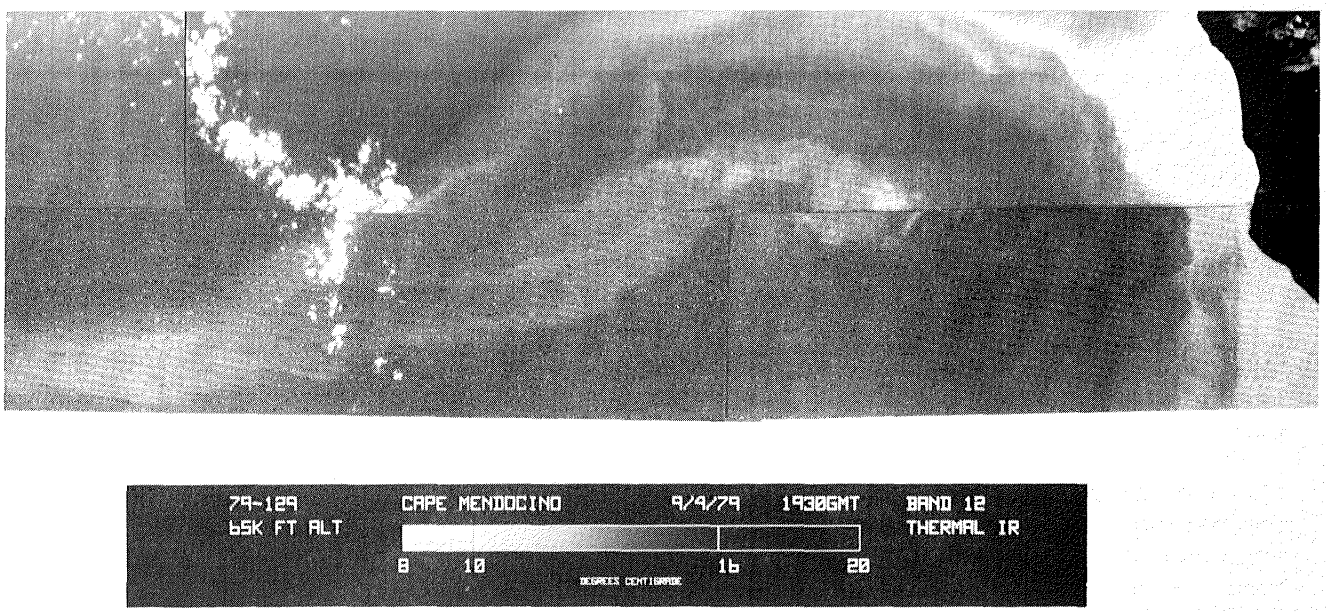


Figure 11.- Mosaic of U-2 thermal imagery (10.5-12.5 μm) off Cape Mendocino; 1917 to 1944 GMT, September 4, 1979.

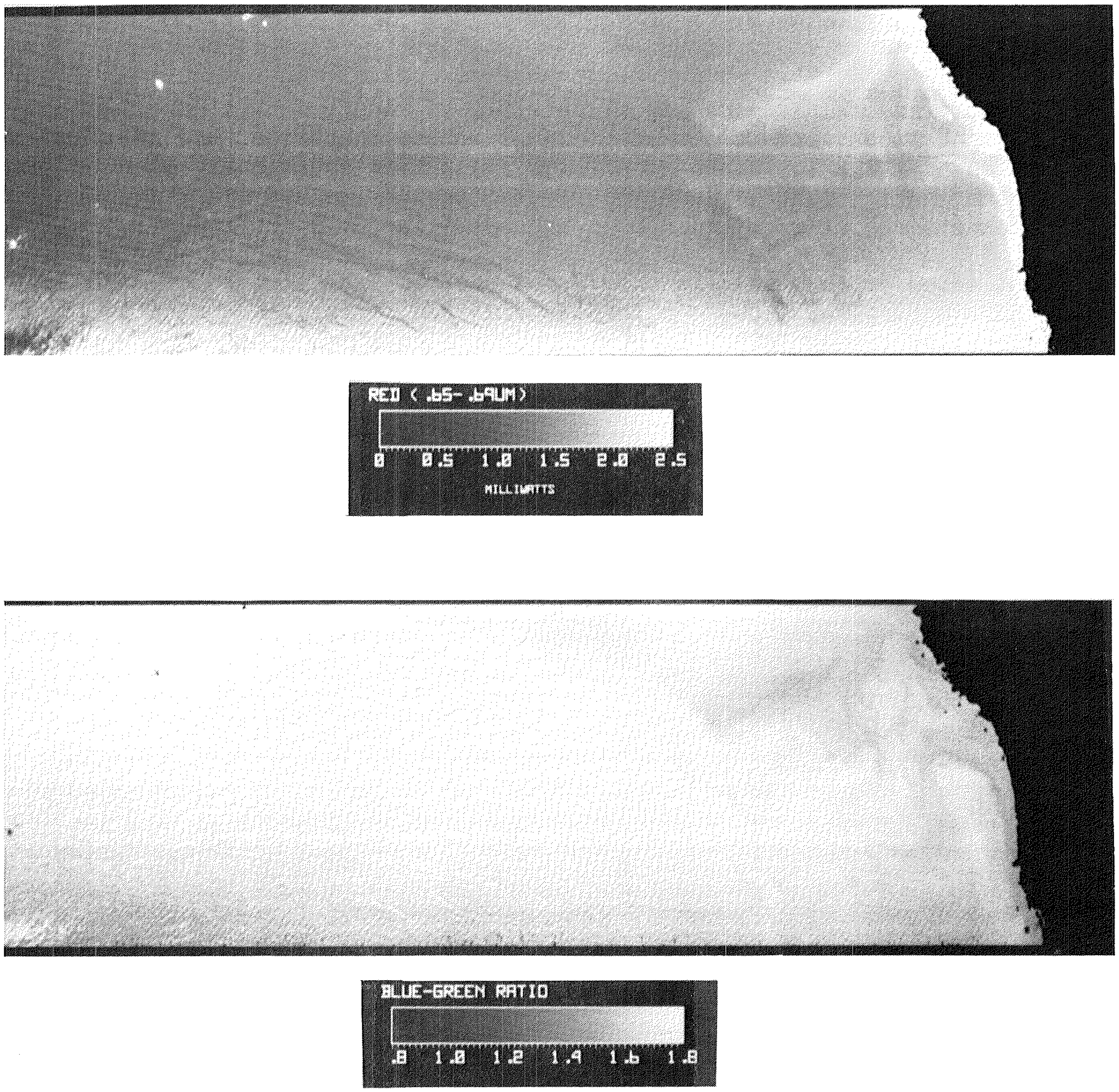


Figure 12.- Northern U-2 flightline imaged in red spectral region and blue/green ratio.

IV. AIRBORNE RADIATION THERMOMETRY FROM THE U.S. COAST GUARD C-130 AIRCRAFT

Airborne Radiation Thermometry (ART) was conducted over the Cape Mendocino study area by the U.S. Coast Guard using a Barnes Engineering, Inc. PRT-5 Precision Radiation Thermometer. The instrument was flown in a C-130 aircraft at a nominal altitude of 150 meters. At this altitude, the instantaneous ground coverage of the instrument is approximately 5 m. The PRT-5 passband extends from 9.5-11.5 μm. Field calibrations of the equipment were made during each flight. Previous experience with this method of calibration has shown precision to be on the order of 0.2°C, and accuracy to be within ±0.5°C.

The flight plan was based on recent satellite coverage of the upwelling feature. The flight lines were constructed normal to the feature at the various points of intersection. Navigation was accomplished using long range navigation (LORAN), tactical air navigation (TACAN), and an Inertial Navigation System. Navigational error was of the order of ±1.0 km. The flight path is shown in figure 3.

Data collected during the flight were transferred from a strip chart to a geographic base map by two methods. The first method employed crossing points for each full degree of temperature, which were identified and plotted on the base map. In the second method, temperatures were read and plotted at 5 km intervals along the track. The temperature fields derived using these two methods were independently contoured and then compared. No significant differences were found. The final temperature field is shown in figure 13.

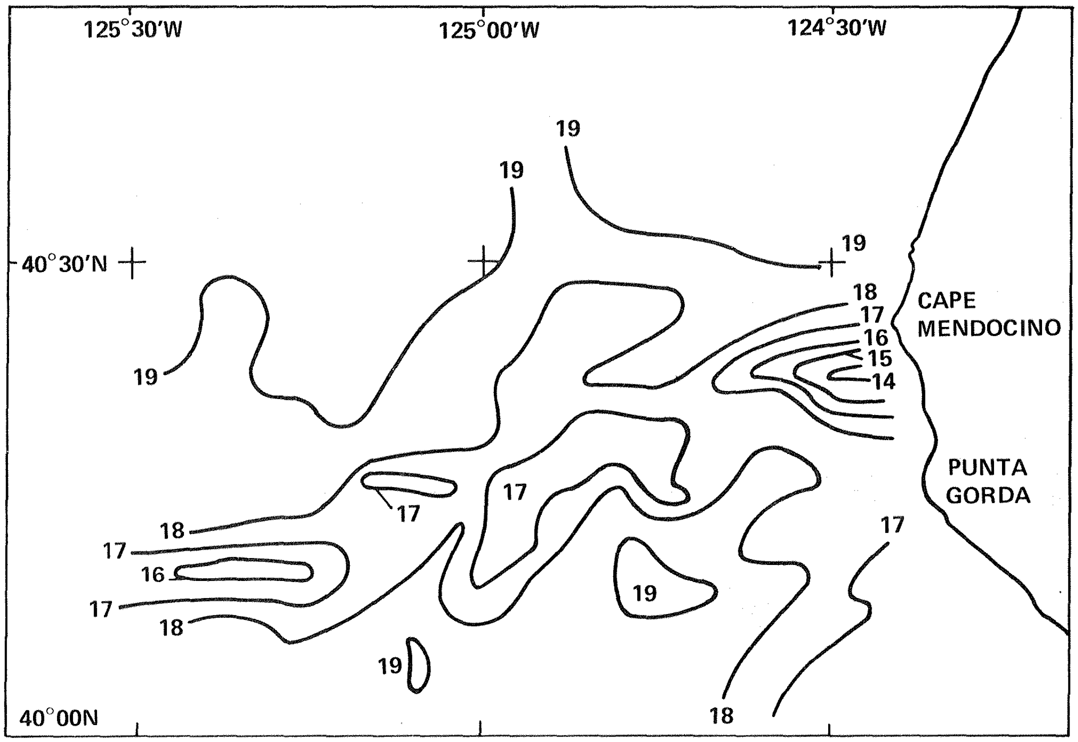


Figure 13.- Map of sea surface temperatures constructed from ART data.

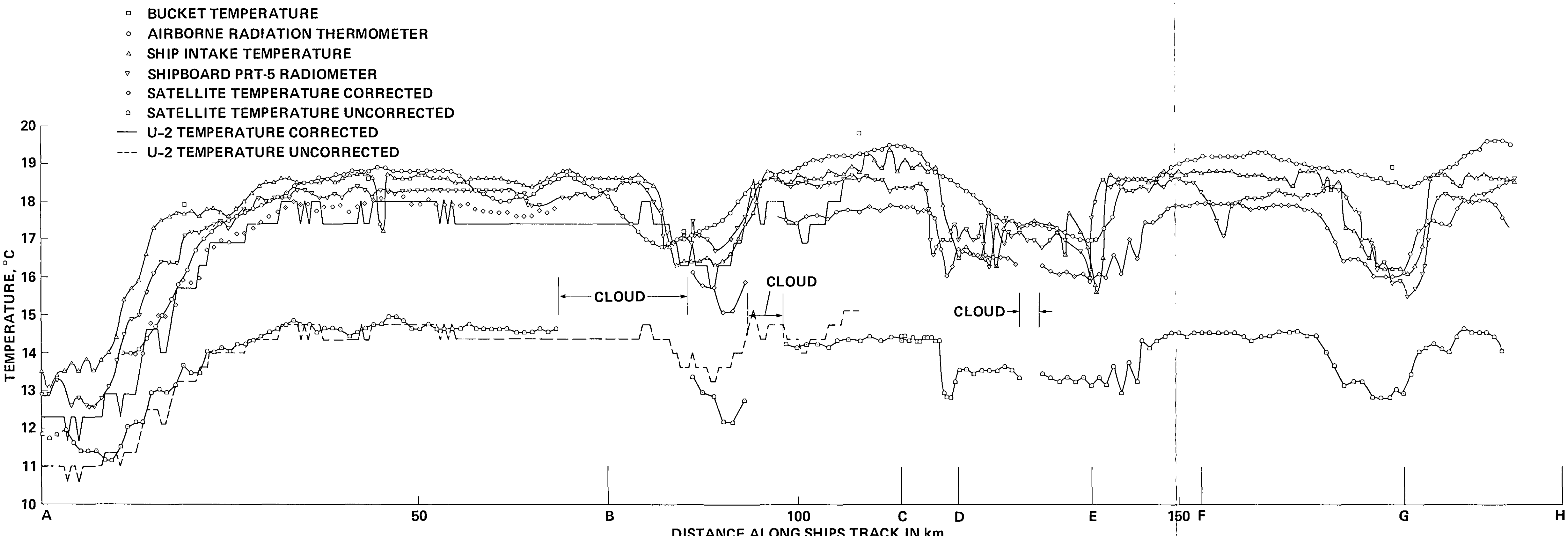
Temperatures ranged from 14°C near shore to 19.5°C outside the feature. In the next section, the Coast Guard ART data are compared with other data collected during the experiment.

V. COMPARISON OF SHIP, SATELLITE, AND AIRCRAFT DATA

Derived sea surface temperatures from ship, satellite, and aircraft are compared in this section and are shown in figure 14.

Continuous records of temperature from the ship's intake thermometer at 4 m depth, and the shipboard PRT-5 radiometer, were digitized at approximately 1 km

Figure 14.- Sea surface temperatures along ship's track from ship, satellite, and aircraft measurements.



increments. These temperatures are also plotted in figure 14 as a function of distance along the ship's track. Bucket temperatures have also been plotted, where available. Calibrated radiometric temperatures for each picture element from the 10-bit satellite data of NOAA-6 orbit 981 are also plotted along the ship's track. Discrete temperature values were extracted from the U-2 aircraft thermal imagery at 1 km intervals along the ship's track and are also plotted. ART data from the Coast Guard C-130 aircraft were obtained at approximately 1 km increments and are likewise plotted.

For the satellite data, Earth location accuracy of the individual pixels was a major concern. The ship's track was superimposed on a rectified satellite image by using a Bausch and Lomb Zoom Transfer Scope wherever the coastline provided a geographic reference. Alignment between the satellite image and the ship's track is estimated to be within a few pixels (≈±3 km).

It was necessary to correct the satellite and the U-2 data for non-unit atmospheric transmittance. These corrections were calculated from shipboard sounding temperature and moisture data taken inside the upwelling feature, midway along track BC (fig. 2). Measurements of temperature and relative humidity were taken at 30 levels between the surface and 100 millibars. At higher levels, values of temperature and relative humidity were taken from the U.S. Standard Atmosphere (ref. 10).

LOWTRAN 4 was used to calculate atmospheric transmittance for the thermal infrared bands (ref. 11). This program employs a numerical evaluation of the radiative transfer equation averaged over spectral intervals of 20 cm^{-1}. The calculations indicate that atmospheric attenuation is sensitive to the boundary temperature (i.e., sea surface temperature). Small differences were found between the corrections for the satellite data and the U-2 data and were mainly due to (1) the different radiometric passbands of these sensors, and (2) the residual atmosphere above the U-2 aircraft. No atmospheric corrections were made to the low altitude Coast Guard ART data.

Corrected sea surface temperatures for both satellite and U-2 data were calculated by using LOWTRAN 4, and these results are also plotted in figure 14. In general, the agreement between remotely-sensed sea surface temperatures and surface truth temperatures appears to be within 1°C.

Areas where the ship crossed the upwelling feature are apparent. Over most of the track, ship intake temperatures appear to be slightly higher than the shipboard PRT-5 measurements. Generally, the ART temperatures are slightly higher than the corrected satellite and U-2 temperatures. To examine the temperature data in more detail, the records were resampled at a uniform interval. The means and standard deviations for each data set were then computed. These statistics are summarized in the following table:

TABLE 2.- MEAN VALUES AND STANDARD DEVIATIONS OF DATA SETS

Data set	Mean	Standard deviation	Sample size
1- Corrected satellite temperature	17.19	0.90	156
2- Shipboard PRT-5 radiometer	17.49	1.38	194
3- Ship intake temperature	17.81	1.35	194
4- Corrected U-2 temperature	17.26	.87	92
5- Airborne Radiation Thermometer	18.23	1.08	184

Linear correlation coefficients for various pairs of data sets were calculated to evaluate the degree of correlation between remotely-sensed sea surface temperatures and the surface truth data. In the following table, the satellite and airborne measurements are compared to the shipboard measurements, and to each other.

TABLE 3.- LINEAR CORRELATION COEFFICIENTS BETWEEN DATA SETS

Data sets	Linear correlation coefficient
1 and 2	0.79
1 and 3	.81
1 and 4	.97
1 and 5	.85
2 and 3	.93
2 and 4	.89
2 and 5	.71
3 and 4	.91
3 and 5	.67
4 and 5	.88

These correlation coefficients are all statistically significant at a confidence level of 99.0% or greater.

When the satellite and U-2 radiometric temperatures are atmospherically corrected, the resulting values are still slightly lower than either of the shipboard measurements of sea surface temperature (fig. 14). Additionally, the shipboard PRT-5 surface temperatures are about 0.3°C lower on average than the ship intake temperatures. However, they are highly correlated (0.93). These differences are due, in part, to the non-unit emissivity of the sea surface. As a result, surface temperatures measured radiometrically are typically a few tenths of a degree cooler than corresponding immersion temperatures (ref. 12). Part of these differences may also be due to the relatively broad passband employed by the satellite and U-2 sensors (ref. 13). An ideal passband was assumed in the calculations of atmospheric attenuation, although the Planck function, as well as the instrument response function, vary over the spectral interval of interest (10.5-11.5 μm).

The aircraft ART measurements are generally slightly higher than the shipboard and satellite measurements of sea surface temperature, although the average difference in mean temperatures between the ART and the ship (ship intake) is still less than 1°C. The ART temperatures show generally lower correlations with the shipboard temperatures than the satellite or the U-2 data. Uncertainties in spatial alignment between data from ship, satellite and airborne platforms also contribute to a reduction in correlation between the data sets.

It was also the purpose of this experiment to compare, where possible, remote measurements of surface temperature with the subsurface thermal structure. Expendable Bathythermograph temperature profiles were used to construct vertical temperature sections along the ship's track. One vertical section along track line BC is shown in figure 15. This section was chosen because it clearly crossed the major upwelling feature. Along this transect, isotherms down to a depth of 30m rise toward the surface. This thermal structure is suggestive of active or relic upwelling in this area.

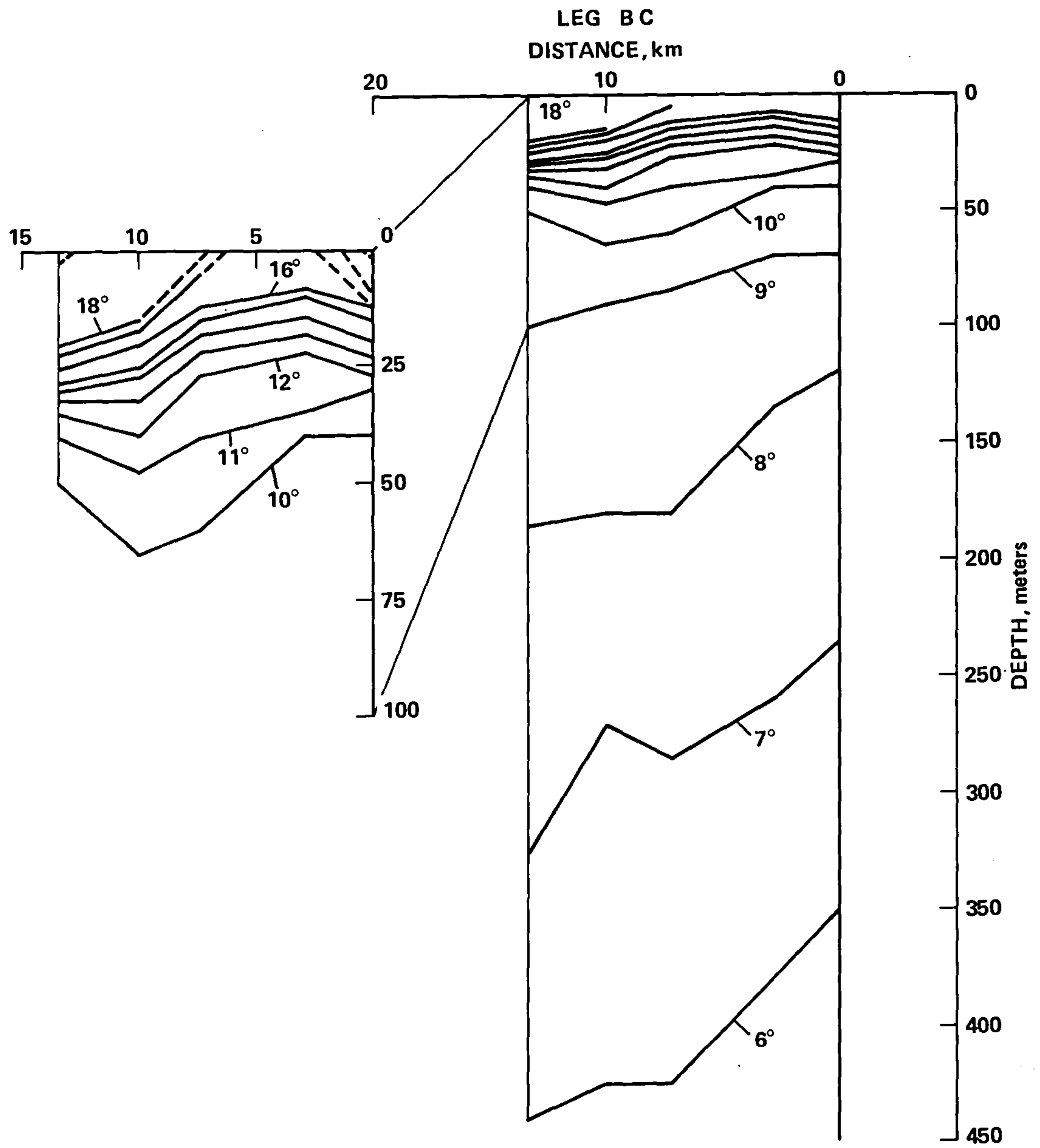


Figure 15.- Vertical temperature section constructed from XBT data along track line BC.

CONCLUDING REMARKS

The results presented here indicate that, under the environmental conditions that existed during this experiment, remote sensing techniques can be used to detect, delineate, and follow the evolution of surface patterns associated with coastal upwelling. Each of the diverse remote sensing methods used herein provided sufficient accuracy to accomplish these objectives.

Estimates of the accuracy of the remote measurements of sea surface temperatures made during the experiment were on the order of 1°C, based on comparisons with shipboard data acquired over the same area and at approximately the same time. Although correlations between the remotely-sensed and the shipboard temperature were generally high, they might have been even higher if the remotely-sensed data could have been more accurately registered and if it had been acquired at exactly the same time.

REFERENCES

1. Squire, J. L.: Measurements of Sea Surface Temperature on the Eastern Pacific Continental Shelf using Airborne Infrared Radiometry. U.S. Coast Guard Oceanographic Report No. 47, CG373-47, 1971, p. iii.

2. Stevenson, M. R.; and Miller, F. R.: Application of Satellite Data to Problems in Fishery Oceanography. Inter-American Tropical Tuna Commission Final Report, 1975.

3. Stevenson, M. R.; Miller, F. R.; and Kirkham, R. G.: Comparison of NOAA-3-4 VHRR Imagery and LANDSAT Multi-spectral Scanner Images with Marine Resource Measurements. Inter-American Tropical Tuna Commission Final Report, 1976.

4. Stevenson, M. R.; and Kirkham, R. G.: Coastal Zone and Open Ocean Observations from NOAA Satellite Very High Resolution Radiometers. Inter-American Tropical Tuna Commission Final Report, 1977.

5. Tabata, S.; and Gower, J. F. R.: A Comparison of Ship and Satellite Measurements of Sea Surface Temperatures off the Pacific Coast of Canada. J. Geophys. Res., vol. 85, no. C11, 1980, pp. 6636-6648.

6. Bernstein, R. L.; Breaker, L. C.; and Whritner, R.: California Current Eddy Formation: Ship, Air, and Satellite Results. Science, vol. 195, 1977, pp. 353-359.

7. Naval Weather Service Detachment: Climactic Study of the Near Coastal Zone West Coast of the United States. Director, Naval Oceanography and Meteorology, 1976.

8. Robinson, M. L.; and Bauer, R. A.: Atlas of North Pacific OceanMonthly Mean Temperatures and Mean Salinities of the Surface Layer. Naval Oceanographic Office Publication NOO RP-2, 1976.

9. Schwalb, A.: The TIROS-N/NOAA A-G Satellite Series. NOAA Tech. Memo. NESS 85, 1978.

10. National Aeronautics and Space Administration, U.S. Air Force, and the U.S. Weather Bureau; U.S. Standard Atmosphere, 1962. U.S. Government Printing Office, 1962.

11. Selby, J. E. A.; Kneizys, F. X.; Chetwynd, J.H.; and McClatchey, R. A.: Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 4. Air Force Geophysics Laboratory, AFGL-TR-78-0053, Environmental Research Papers, No. 626, 1978.

12. Saunders, P. M.: The Temperature at the Ocean-Air Interface. J. Atmos. Sci., vol. 24, 1967, pp. 269-273.

13. Weinreb, M.P.; and Hill, M.L.: Calculation of Atmospheric Radiances and Brightness Temperatures in Infrared Window Channels of Satellite Radiometers. NOAA Tech. Rpt. NESS 80, 1980.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-86712		

4. Title and Subtitle	5. Report Date
SEA SURFACE AND REMOTELY SENSED TEMPERATURES OFF CAPE MENDOCINO, CALIFORNIA	September 1985
	6. Performing Organization Code
7. Author(s) L. C. Breaker (Nat'l Oceanic and Atmos. Admin., Redwood City, CA); J. C. Arvesen (Ames Research Center); D. Frydenlund (US Coast Guard, San Francisco, CA); J. S. Myers (ATAC, Moffett Field, CA); and K. Short (Northwest Ocean Services Center, Seattle, WA)	8. Performing Organization Report No. 85208
9. Performing Organization Name and Address Ames Research Center Moffett Field, CA 94035	10. Work Unit No.
	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code 640-12

15. Supplementary Notes

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16. Abstract

During September 3-5, 1979, a multisensor oceanographic experiment was conducted off Cape Mendocino, California. The purpose of this experiment was to validate the use of remote sensing techniques over an area along the U.S. west coast where coastal upwelling is known to be intense. Remotely sensed multispectral data, including thermal infrared imagery, were collected above an upwelling feature off Cape Mendocino. Data were acquired from the TIROS-N and NOAA-6 polar orbiting satellites, the NASA Ames Research Center's high altitude U-2 aircraft, and a U.S. Coast Guard C-130 aircraft. Supporting surface truth data over the same feature were collected aboard the National Oceanic and Atmospheric Administration (NOAA) ship, OCEANOGRAPHER. Atmospheric soundings were also taken aboard ship.

The results indicate that shipboard measurements of sea surface temperatures can be reproduced within 1°C or better through remote observation of absolute infrared radiance values (whether measured aboard the NOAA polar orbiting satellite, the U-2 aircraft, or the Coast Guard aircraft) by using appropriate atmospheric corrections. Also, the patterns of sea surface temperature which were derived independently from the various remote platforms provided a consistent interpretation of the surface temperature field.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Remote sensing Oceanography Sea-surface temperature Coastal upwelling California current	Unlimited Subject category - 48

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	29	A03

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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