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Arabian Sea Project of 1980
The Development of Infrared Imagery Technique
ONRWEST Report 81-3

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Cover: Infrared (3.55 to 3.53 μm) image of the Gulf of Oman, Arabian Sea, obtained by NOAA-6 Satellite on 30 May 1980 and enhanced in the Scripps Institution of Oceanography Remote Sensing Facility.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ONRWEST Report 81-3	2. GOVT ACCESSION NO. A102 576	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ARABIAN SEA PROJECT OF 1980: THE DEVELOPMENT OF INFRARED IMAGERY TECHNIQUE		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ben J. Cagle and Robert Whritner		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Western Regional Office 1030 East Green St., Pasadena, California 91106		12. REPORT DATE April 1981
		13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Chief of Naval Research Department of the Navy Arlington, Virginia 22217		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DTIC ELECTE AUG 7 1981 D

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Infrared Imagery
Arabian Sea
Remote Sensing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A technique was developed for determining the mesoscale features of the Arabian Sea. This technique utilizes infrared image data recorded by satellite. These data were enhanced and interpreted at the Scripps Institution of Oceanography Remote Sensing Facility.

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S/N 0102-LF-014-6601

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ONRWEST 81-3

ARABIAN SEA PROJECT OF 1980--THE DEVELOPMENT

OF

INFRARED IMAGERY TECHNIQUE

This report was prepared by
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and
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Office of Naval Research
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1030 East Green Street
Pasadena, CA 91106

April 1981

APPROVED:

LEWIS LARMORE
Technical Director

SUMMARY

An effort was made to describe the mesoscale features of the Arabian Sea. After surveying the literature and making several attempts with the Defense Meteorological Satellite Program (DMSP) receivers, the attention was turned to the NOAA-6 satellite. Tape recorders were programmed to record the high resolution infrared radiometer on this satellite for periods beginning in mid-March 1980 and continuing at random intervals through November 1980. The tapes containing these images were processed at the Scripps Institution of Oceanography Remote Sensing Facility (SRSF) in La Jolla.

The technique for enhancing and interpreting these satellite infrared images was developed at SRSF. Quick-look images, supplied by the National Environmental Satellite System (NESS) of the National Oceanic and Atmospheric Administration (NOAA), were used to select these days that would provide relatively cloud-free views of northern portions of the Arabian Sea. These recordings were then selectively processed at SRSF.

The data to be analyzed were digitized and reformatted, then rectified and displayed for areas of interest. From this low-resolution display, cloud-free portions were selected for analysis. These portions were enlarged to cause a 563 kilometer square to fill the display, then calibrated and mapped repeatedly to cover all areas of interest. A complete mosaic of all square areas was produced to show the sea surface temperature structures for selected days in 1980.

SUMMARY

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Acknowledgements:

This development of satellite infrared imagery technique was fostered by Dr. Robert Stevenson, Mr. Ben Cagle, and Mr. Robert Lawson of ONRWEST, with the assistance of many people, including members of the Naval Research Reserve Unit attached to ONRWEST (primarily CDR N. Persson, CDR M. Morrison, and LCDR P. Henshaw). The lead capability in the technique was due to Mr. Robert Whritner of the Scripps Institution of Oceanography. This project was funded by ONR Headquarters, the Naval Science Advisory Program, and ONRWEST. This report was typed and proofread by Mrs. JoAnn Harper of ONRWEST.

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The Arabian Sea is bounded on the west by the Arabian Peninsula, on the north by the coasts of Iran and Pakistan, and on the east by the coast of India. Bathymetry is provided down to 3000 meters to illustrate the rapid falloff of the shelf in some areas. The Oman Basin is partially closed by the Murray Ridge with an opening to the Arabian Sea near the Arabian Coast.

Figure 2. Socotra Eddy Field.

Warm-core eddies are observed north and east of the Island of Socotra. The possible dome of a cold-core eddy can be seen to the northeast.

Figure 3. Temperature Profiles for Mid-Summer 1977.

These data, obtained from Dr. John Bruce of the Woods Hole Oceanographic Institution, were obtained on a ship of opportunity. They are typical of data obtained for several years and analyzed for monthly averages. The track of the ship is given in Figure 4.

Figure 4. Tanker Track for Figure 3.

Several tankers, with some variation in ship tracks, were used in this ship-of-opportunity program, and the average track is given here for the data in Figure 3.

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This image was recorded on 30 May 1980 as the satellite passed over the Arabian Sea. It has not been rectified or significantly enhanced.

Figure 7. Expanded Infrared Image.

This full-resolution image was expanded to show individual pixels. Each pixel portrays a 1.1 km square on the ocean surface. The linear feature observed near the center of the cold clockwise flow pattern of Figure 8 is thought to be a ship's wake.

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Figure 9. Enhanced Infrared Image of Area Off Arabian Coast.

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Figure 11. Enhanced Infrared Image of Arabian Sea Area Southwest of Karachi, 18 March 1980.

This area, in the northeast corner of the Arabian Sea, appears to have lines of small vortices along shear lines that lie over, and south of, a large submarine canyon, entitled the Indus Swatch. Warm water is slowly transported northward along the edge of the shelf. Cool water persists on the shelf and a southward flow of cool water appears farther offshore. In Figures 11, 12, and 13, the overlay was photographed with the image to indicate the interpretations.

Figure 12. Enhanced Infrared Image of Arabian Sea Area Southwest of Karachi, 19 March 1980.

This view follows that of Figure 11, and shows the shear line and small vortices.

Figure 13. Enhanced Infrared Image of Arabian Sea Area Southwest of Karachi, 20 March 1980.

This image follows that of Figures 11 and 12, and again shows the shear lines and small vortices. This three-day sequence shows some change in the evolution of the features.

INTRODUCTION

Infrared imagery taken from satellite data provides a synoptic representation of the surface expressions of many mesoscale features in an ocean area. It is important to consider the use of satellite infrared imagery, especially in areas where few oceanographic data exist, for describing these mesoscale structures. Published data give little insight into the mesoscale structures of the Arabian Sea, and large expenditures in time and money would be required to obtain definitive data at the required scales. Thus, an effort has been made to achieve a qualitative description of ocean features in the Arabian Sea by means of enhanced satellite infrared imagery.

Although satellite infrared imagery of ocean areas is enhanced, interpreted, and disseminated by other organizations, some of the techniques developed in this project differ from standard practices and lend themselves to oceanographic descriptions of remote ocean areas, especially when the time to achieve the descriptions is short. Thus, the techniques discussed here focus on a procedure for timely acquisition, processing, and interpretation of satellite data for a strategically located remote area of the world's oceans.

Ground-truth data for satellite imagery still require the classical methods of oceanographic data collection. It is a slow process to gather published and unpublished data for verifications of the satellite interpretations, and improvements in the interpretations come with each additional set of data. Consequently, these evaluations of the Arabian Sea imagery are preliminary at this time, and this report deals primarily with the development of techniques rather than the verification of the infrared data analyses. Further studies of seasonal effects on the ocean and the validity of these analyses will be published later.

BACKGROUND

In January 1980, members of ONRWEST began to gather unpublished oceanographic information to offer to the U.S. Fleet in the Indian Ocean. This effort concentrated on the Arabian Sea (see Figure 1). In a cooperative effort, a brief review of the published and unpublished literature was prepared by Dr. Robert Knox of the Scripps Institution of Oceanography and published by ONRWEST in 1980. He found that most of the oceanographic descriptions of the Arabian Sea were derived from meteorological information. There were no data to support the description of mesoscale ocean structures, and only brief information existed on upwelling features along coastlines.

Visits were made in early 1980 to appropriate Naval command staffs in San Diego and Pearl Harbor to discuss the Arabian Sea environmental problems, the scientific knowledge residing in the Navy related to those problems, and an approach for coping with selected problems. These were followed by visits to the Naval Ocean Systems Center, Naval Underwater Systems Center, Naval Ocean Research and Development Activity, Naval Oceanographic Office, Scripps Institution of Oceanography, University of Hawaii, and Woods Hole Oceanographic Institution, as well as the Ocean Science and Technology Division of ONR. Other institutions, such as the University of Miami and Texas A&M University, were contacted as possible sources of information.

The general concept which emerged was that the Arabian Sea is probably bounded by some gently flowing currents driven in the winter by the Northeast Monsoon and in the summer by the Southwest Monsoon. Ocean eddies, known to form in summer near the Island of Socotra, were thought to drift majestically along the Arabian Peninsula and across to the coast of India. There were no data to support these concepts, but there was similarity in the opinions heard in most places. It was thought that mesoscale features would not be sharply defined or significant, but that the eddy kinetic energy could be high.

Computer tapes containing NOAA-6 satellite infrared images were borrowed from Dr. Otis Brown, University of Miami, who had recorded them on a trip to Mombasa to study the Somalia Current. These tapes were processed for the northernmost extent of the ocean coverage, and known eddies were revealed. An example is given in Figure 2 showing the eddy field off the Island of Socotra on 19 August 1979. These images confirmed the concept that eddies form near Socotra and may possibly drift to the northeast.

Extensive efforts were made to obtain tape-recorded images from the Defense Meteorological Satellite, but for various reasons no images were ever obtained. The next step was to explore the possibility of using the high-resolution (AVHRR), tape-recorded data from the NOAA-6 satellite. It became possible to schedule this satellite tape recorder for several days each month beginning in mid-March 1980. The first quick-look images showed strong mesoscale features. These early taped images were processed and the usual steps in rectification and enhancement were used.

SURVEY OF INFORMATION

There have been several oceanographic cruises in the Arabian Sea. Typically, an oceanographic ship would come out of the Gulf of Aden and steam directly east or turn to the southeast. Enough information was obtained north of 15°N to conclude that the eddy kinetic energy in the Arabian Sea was fairly high.

One of the better data sets on the Arabian Sea was obtained by Dr. John Bruce, Woods Hole Oceanographic Institution, from a ship-of-opportunity program. Bruce had an arrangement with a foreign technician who rode supertankers into and out of the Gulf of Oman. The primary purpose of the program was to obtain data on the Somalia Current and eddy fields south of 10°N. Most of the time, however, the technician continued taking expendable bathythermograph (XBT) readings northward to about 22°N, near the entrance to the Gulf of Oman. Sufficient data were obtained in four and one-half years to present monthly average temperature profiles along the ship route. An example of one of these profiles is given in Figure 3. This temperature structure supports the concept of a series of eddies, or frontal-like features, along the track of these ships; the track itself is indicated in Figure 4.

No other satellite imagery of the Arabian Sea has been found in the literature.

TECHNIQUE

The NOAA-6 satellite has three bands in the infrared spectrum. Band number three, at 3.55 μm to 3.93 μm, permits the best view of the ocean surface, because this band is least affected by atmospheric moisture contamination when the field of view is free of clouds. This band was most useful and other bands at higher wavelengths were badly contaminated when tropical moisture conditions existed. Taped AVHRR data were scheduled for approximately ten days each month with the hope of getting at least one or two days in each period that would be cloud free. A list of the days for which reasonably clear images of the ocean surface were obtained is given in Figure 5.

A brief description of the methods used in recording satellite data may be helpful to those who need to schedule and utilize satellite tape recorders. There are twelve tape recorders on the NOAA-6 satellite. The scheduling of each tape recorder is done in advance by NOAA for those submitting valid requests. One tape recorder has the capacity to store an image extending approximately 35° in latitude. Because the pass may not go directly over the area of maximum interest, the unrectified, quick-look image is distorted due to the curvature of the earth. An example of a typical quick-look image is given in Figure 6.

Data from the tape recorders are dumped when the satellite passes over a suitable ground receiving station, such as the one in Gilmore Creek near Fairbanks, Alaska. An electronic turnaround of this recording is performed, and the data are immediately beamed to a geostationary satellite on the Equator (Domsat), and again retransmitted without storage to suitable receivers. One such receiver is operated by NOAA/NESS on the East Coast, with the images being stored on computer discs in Suitland, Maryland. Both quick-look images and duplicate computer tapes can be obtained from NOAA, the former being used to select days in which the atmosphere is sufficiently clear to warrant the processing of a tape. Tapes are then ordered and processed.

The first step in processing was to perform a geometric transformation to rectify the image. This minimizes the distortion resulting from earth curvature and the fact that the satellite may not have passed directly over the area of interest. Various enlargements then can be tried to achieve a reasonable view of a more specific area of interest. Even the quick-look and first enlargements without significant enhancement are sufficient to reveal thermal features in the surface of the ocean.

The next step in image processing was to experiment with various temperature scales. A suitable contrast was chosen to accommodate the ability of an observer to distinguish features by means of shadings in greys from white to black. These grey scales were then spread over a known scale of temperature differences. A span of 10°C was usually sufficient to identify major features for further enhancement. A reasonable estimate as to the apparent surface temperature of the ocean was sufficient for a first choice on the center temperature of this 10°C difference scale. That center temperature was then raised or lowered in value to reveal features which were warmer or cooler than demonstrated by the first estimate of ocean surface temperature.

Because there is a large range in ocean temperatures in the Arabian Sea, from the Gulf of Oman southward toward the Equator, it was necessary to continue further in the enhancement process. Confining the field of view to a small area was helpful in limiting the temperature range that had to be considered. After some trial and error, a full-resolution square of 512 x 512 pixels was chosen as the basic image because of some limitations in the display equipment. In this case the field of view represented approximately a 560-kilometer square of the Arabian Sea.

The program in the computer automatically scaled the entire temperature range of any image to the total number of possible grey shades from white to black. A further narrowing of the temperature range resulted in saturation at both the cold (white) and warm (black) ends, with features being revealed in some portion of the field of view. Thus, a small portion of the thermal window could be examined in detail for features in the sea-surface temperatures. A convenient approach was to spread all grey scales across a 2°C total temperature range. Then the center temperature was varied slowly from a cool value to a warm value, or vice versa, to examine ocean features as they appeared and disappeared. The effect when viewing the display was similar to a curtain rising on a screen. Features would begin to appear in the colder regions of that portion of the ocean and go through a sharpening and fading sequence as the rising "center temperature" revealed adjacent features. In this fashion, greatly detailed mesoscale structures could be viewed and studied.

Programming in the SRSF computer permits the operator to assign histograms across any line in the field of view of the display. Using this method, lines were laid across many of the features, thereby revealing in great detail the minute structures observed during the enhancement process. These histograms give an immediate quantitative value of the differences in temperature across a given thermal feature. Even though the absolute temperature was not known, the relative temperatures and the steepness of the temperature gradients were obtained by this method.

Many of the temperature features were sufficiently small so as to require further enlargement of the image. In some cases, the image was enlarged to the point that the recorded pixels were revealed on the screen. In the case of the NOAA-6 satellite, a pixel represents a field of view at the surface of the earth of approximately 1.1 km in length and width.

An example of an enhanced image enlarged to reveal the pixels is given in Figure 7. This view reveals a linear feature located across a curved oceanographic feature. The differences in temperature represented by the smallest change in grey scales is about 0.2°C. The processing causes a line of pixels to remain one shade of grey until a slight change in temperature causes the line to continue at the next shade of grey. Where successive lines of pixels reveal a linear feature, which cuts across an ocean structure and across the sample direction (related to electronic noise), then the consistency in the change is thought to reveal a real feature. In particular, the linear feature in Figure 7 is thought to be a ship wake. It is lighter in grey shade which means it is colder; and although the width of a wake is not as wide as a pixel, it brings up water of perhaps a few degrees colder than that at the surface. In this case, the water was cold enough to dominate the 1.1-km-square area as indicated by a slight lowering in the average value of temperature in that pixel. The region of the Arabian Sea in which this linear feature was obtained is given in Figure 8. Here the field of view is defined by 512 x 512 pixels in the display, and the wake-like feature can be faintly seen in the area where the extreme enlargement was made for Figure 7.

One of the techniques used to examine linear features or artifacts is not shown in this report. It is a method of substituting false colors for grey shades. In experimenting with false color technique, it was learned that the color separation can be enhanced in maximum contrast to the point that a slight changeover in color can be made to occur exactly on faint linear features. Thus, sliding the center temperature scale was equivalent to sliding the center color of the spectrum of false colors along until the very edge of a faint linear feature is reached. In this manner, the feature can be made to appear much more sharply than by the use of grey scales.

Successive enhancements, zooming to the largest revealed by the pixels and back to the smallest in the overall view of the Arabian Sea, were used to examine the oceanographic thermal features on several scales. Relating these features to their location and possible [illegible] was helpful in optimizing the technique of enhancement and visual study [illegible] of this methodology can be portrayed by photographs in a report, and w[illegible]s still going on in attempts to develop the best means of describing the ocean from this method.

Photographs of the displayed imagery were obtained using a camera in front of the display screen. To obtain an image for photography, it was necessary to open the temperature scale so that the grey shades would reveal a sufficiently broad field of features to photograph. An example of one of these photographs is given in Figure 9. This does not represent the most sensitive thermal features which can be obtained in the SRSF, but shows a compromise in sensitivity and enhancement in order to spread features over the field of view for photography. Also, the photographic process results in some loss of resolution and, of course, the method of printing the images for this report results in additional loss of resolution.

In order to illustrate the interpretations which are drawn from the enhanced images, a sketch of the interpretation of features was prepared on transparent film and presented as an overlay on a photograph of the image. These films could not be reproduced in the publication process; only the overlaid photograph could be reproduced. Thus, Figure 10 is Figure 9 plus overlay.

DATA

The data being worked on were obtained during the relatively clear days listed in Figure 5. The time of each pass by the NOAA-6 satellite for these data is approximately 2000 local time. No visual data were obtained, but the infrared data are sufficient to determine the clarity of the atmosphere for revealing features on the surface of the ocean. Although the data exists for the full field of view of the satellite as it passed over the Arabian Sea, only those portions near the Arabian Coast and in and near the Gulf of Oman have been examined. The enhancement process and analyses are time consuming, so that effort was devoted to these areas where supporting information or ground truth data might be obtainable, such as that in Figure 3. Other supporting information is indirectly embodied in the considerable experience at the SRSF in observing mesoscale features in other ocean areas and verifying them with bathythermograph measurements.

The mesoscale features revealed in these infrared images are distinguishable from atmospheric contamination and artifacts by their persistence from day to day. Also, the previously described enhancement process can be used to examine the relative altitudes of any atmospheric contamination in the field of view.

Although the absolute value of the sea-surface temperature would be of interest in these data, it is not considered necessary. The relative values of temperatures between features and the gradients in temperature near the boundaries of features reveal sufficient information to make qualitative judgments of the mesoscale structures in the field of view.

Because the satellite passes over the area of interest in the early evening, it views the residual effects of daytime heating. When there are light winds and calm seas, the surface heating generated during the day remains until nighttime effects cause it to mix or fade. Regions of low wind and light mixing can be distinguished by surface slicks. The curved, fine-lined features in Figure 8 are patterns of slicks. These slicking patterns, possibly representing very small temperature differences or changes in surface radiance, tend to form lines parallel to the relative flow of near-surface layers and, thus, outline patterns that reveal a synoptic representation of flow. These synoptic flow patterns are instantaneous in time and, therefore, are superimposed on the general drift of the waters. This general drift can be seen in successive days such as those of 18, 19, and 20 March 1980 (Figures 11, 12, and 13). Here the small vortices along the shear line that appears to lie above a large submarine canyon (the Indus Swatch) drift slowly southward in the flow.

Although a qualitative interpretation of the satellite infrared data is sufficient to describe mesoscale features in the Arabian Sea, it is still desirable to obtain supporting data. Expendable bathythermograph records are being sought from ships-of-opportunity in the area for eventual satellite oceanographic analyses.

INTERPRETATION

The development of enhancement techniques for imagery of the Arabian Sea leads eventually to interpretation. Many factors are considered, including the time of day, the sequencing of images, the use of histograms, and variations in the range of temperature for the grey scales available. Other factors also form a part of the interpretation. These include a study of the weather and meteorological conditions existing at the time the image is obtained. Because the ocean responds to atmospheric forcing, the reasonable cause-and-effect relationship is a logical step in verifying the nature of the mesoscale features. Shoreline and ocean bottom topography also play an important role in the generation and location of these mesoscale features.

Upwelling is known to occur along the southeast coast of Arabia and is apparent in all of the images of that region. The upwelling forms near points of land and streams offshore with the flow. These upwelling features, with their associated eddies and plumes (or wedges), appear, to some extent, in all images taken throughout the year. The upwelling, of course, strengthens in the summertime as a result of the strong effects of the Southwest Monsoon.

In general, the mesoscale features being interpreted from these infrared images are influenced by coast effects, bottom topography, depth of the ocean, winds, and ocean currents. These qualitative judgments lead to an interpretation, not only of the strength of the features, but of their probable depth. What few ocean measurements exist, such as those given in Figure 3, support the concept that features observed here from infrared imagery extend to normal depths known for similar features in other oceans. The upwelling and the drift of upwelled water are illustrated by relative motion sometimes associated with lines of shear. One simple form of these interpretations, which are being made for all of the images, is depicted in Figure 10. Drawn to the same scale and overlaid on the printed image, the transparent interpretations are being used in efforts to describe and explain mesoscale features in the Arabian Sea.

RATIONALE AND CONCLUSIONS

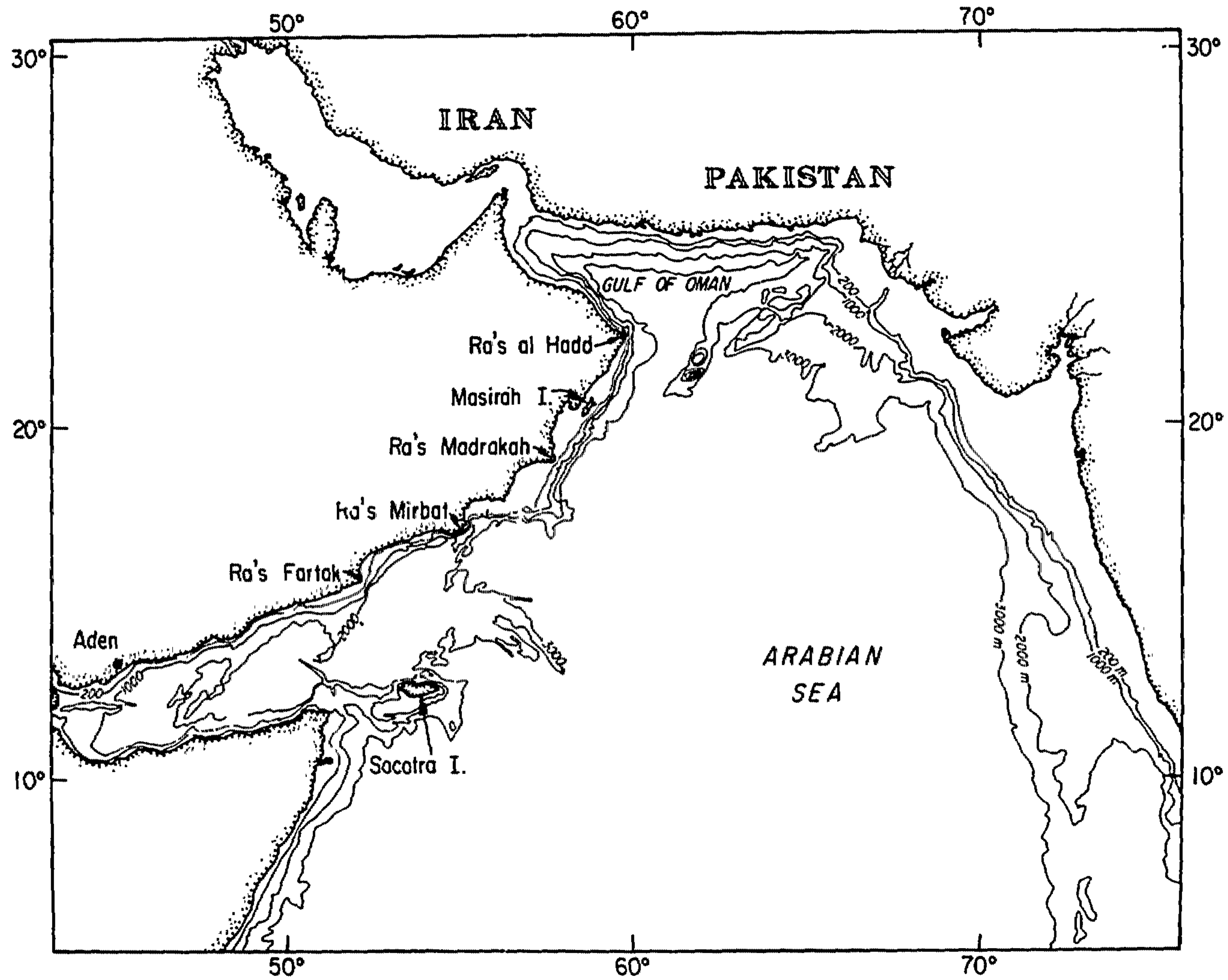
Some of the decisions made in fleet operations involve time scales of a few hours to a few days and space scales of a few tens to a few hundreds of kilometers. These are also approximately the scales of little change in mesoscale ocean features. It is desirable, therefore, to describe these features in the ocean where they influence environmental factors of consideration in tactical operations. While oceanographic mapping at these scales is usually impractical, or may depend on many years and numerous data sets to compile, it is relatively easy to achieve a qualitative description of the mesoscale ocean at these scales by using infrared imagery obtained from satellites. The techniques presented in this report are an example of what can be done to provide a qualitative description of the ocean in a short period of time. As a result, remote areas of interest to oceanographers but not easily predictable in their structure, as was the case for the Arabian Sea, may be quickly and qualitatively evaluated.

The methods of selection, enhancement, interpretation, and communication of these data, developed in this project, can be a guide to the development of a more reliable means for providing descriptions of an ocean area. It is a challenge to adequately explain satellite-derived interpretations of the mesoscale ocean to persons who may need to utilize the information in research or operational decisions. Sketches of ocean features, in terms of their implications in underwater acoustics, can be developed. These sketches could take a form similar to surface analysis charts performed in meteorology for the forecasting of weather. Thus, surface drawings could be created and projected ahead in time as a basis for predicting the features and their implications. Since the mesoscale features of the ocean evolve slowly in time, these surface drawings can be a basis for predicting the features when the ocean is obscured by clouds. Predictive models which make use of the atmospheric and oceanographic forcing functions influencing these features can be utilized not only in creating the surface analysis drawings but also in projecting the movement of features. Work is needed on methods for conveying implications derived from these interpretations of satellite imagery.

An objective of oceanographic research is to gain improved knowledge and understanding of ocean processes, such as the generation and decay of mesoscale features in the upper ocean. There is the possibility of using the techniques developed here to achieve synoptic descriptions of data on ocean processes obtained from ships or moorings.

Infrared bands with wavelengths greater than 4 μm are used in meteorological interpretations of satellite-derived imagery and even in oceanographic interpretations from this imagery in ocean areas having strong thermal signatures and relatively dry atmospheric conditions. The next higher band on the NOAA-6 satellite is used for the study of coastal ocean features in midlatidude areas, and the highest infrared band is used for studies of the Gulf Stream and Kuroshio. However, it was found in this project that atmospheric moisture contamination is severe in bands with wavelengths higher than 4 μm. This contamination exists frequently in tropical ocean areas and can be a significant limitation to the use of higher wavelengths in most temperate ocean areas far from shorelines. The band at 3.5 to 4 μm is thought to be the best choice for studies of ocean features having relatively weak thermal signatures and dimensional scales of tens of nautical miles.

FIGURES



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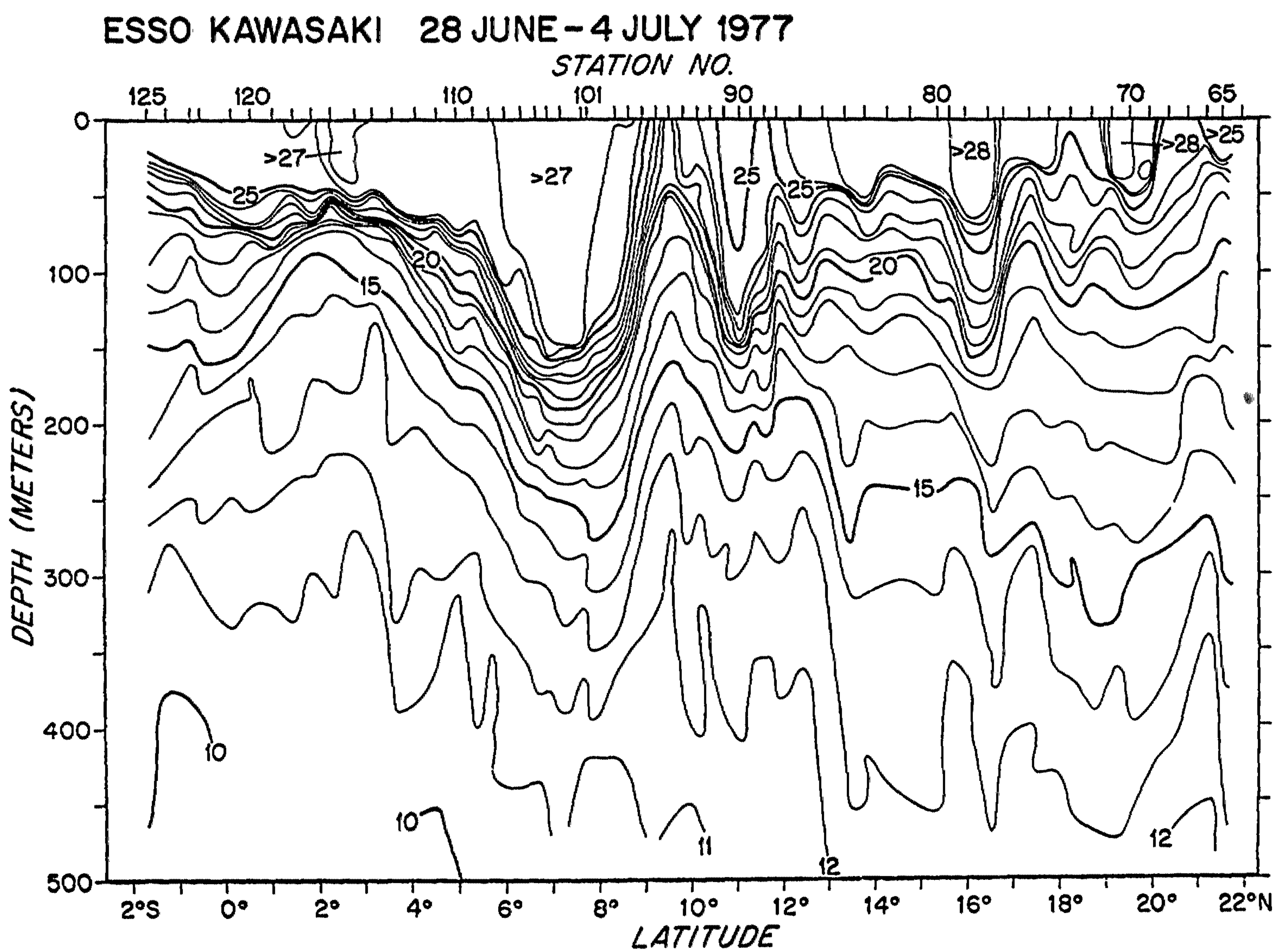

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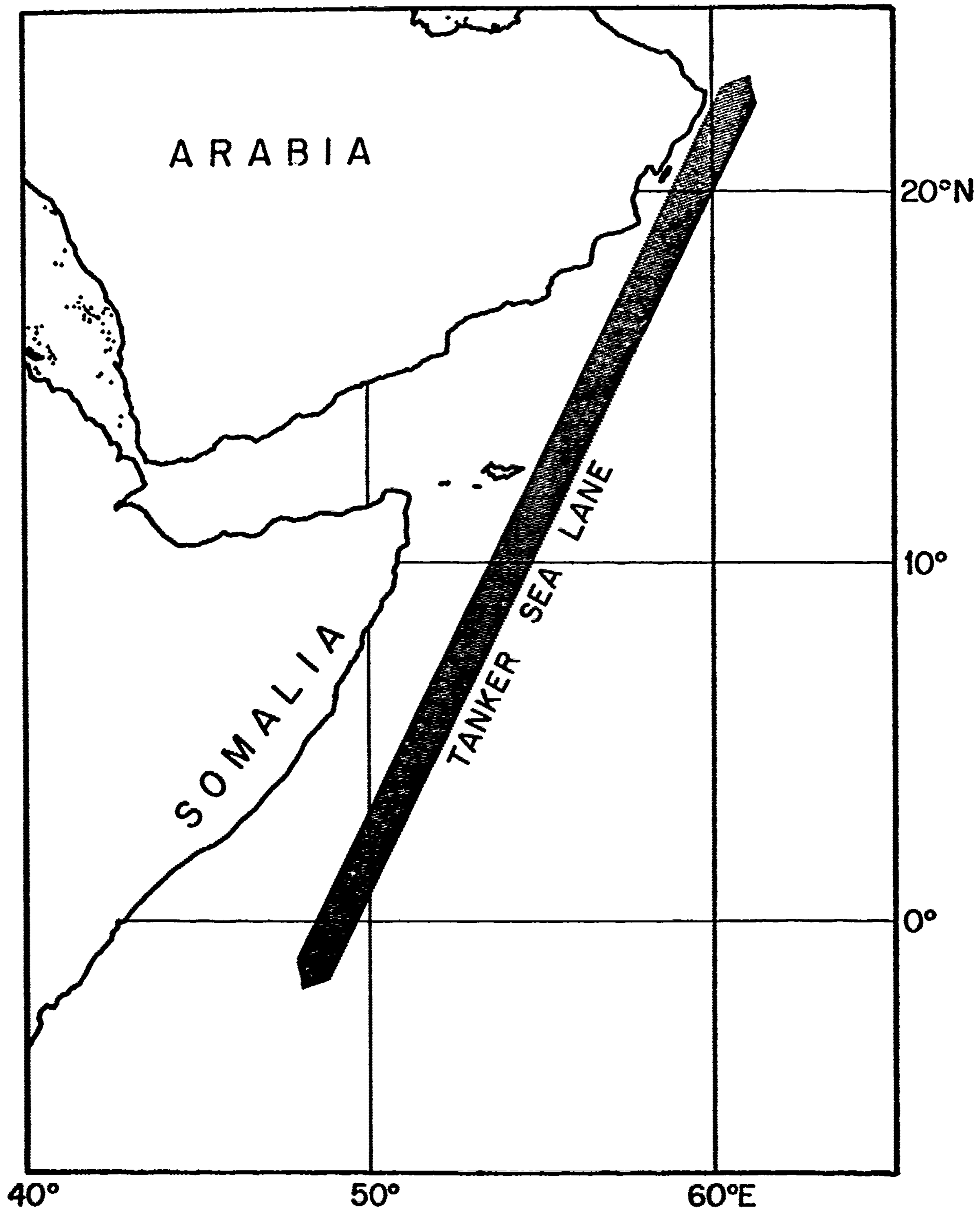

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INFRARED IMAGES NOAA-6, BAND 3, CALENDAR YEAR 1980

Julian Date	Calendar Date	Quick Look	Rectified Image
078	18 Mar	√	
079	19 Mar	√	
080	20 Mar	√	
088	28 Mar	√	√
092	01 Apr	√	√
096	05 Apr	√	
098	07 Apr	√	
102	11 Apr	√	
106	15 Apr	√	√
110	19 Apr	√	
138	17 May	√	
142	21 May	√	√
148	27 May	√	
150	29 May	√	
151	30 May	√	√
272	28 Sep	√	√
274	30 Sep	√	√
300	26 Oct	√	√
330	25 Nov	√	√
332	27 Nov	√	√
335	30 Nov	√	√

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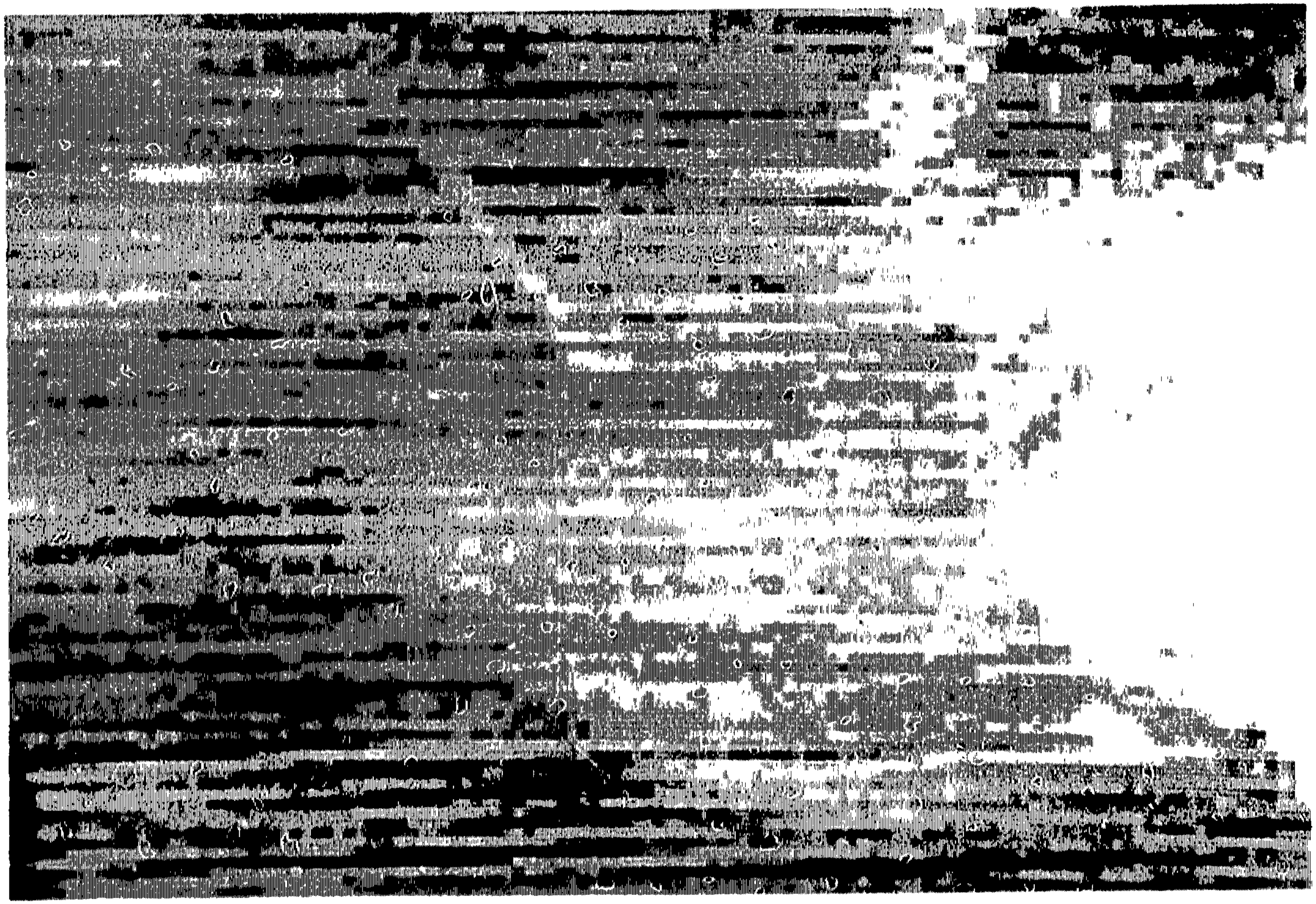

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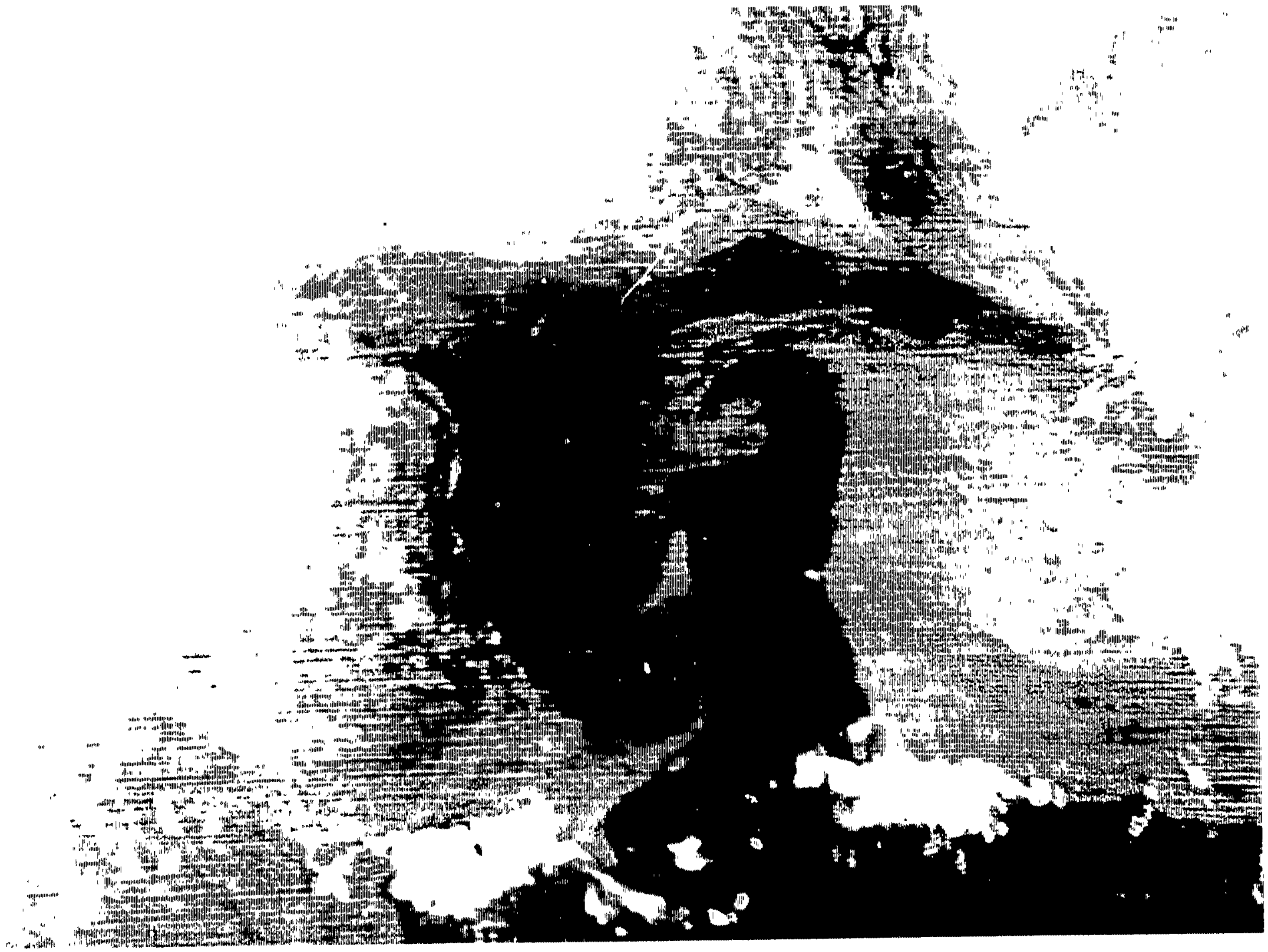

Figure 8. Enhanced Infrared Image.

This enhanced view of a 512 x 512 pixel area reveals a large cold clockwise gyre in the northeastern portion of the Arabian Sea. The linear feature was easily discernible during enhancement for both Figures 7 and 8.

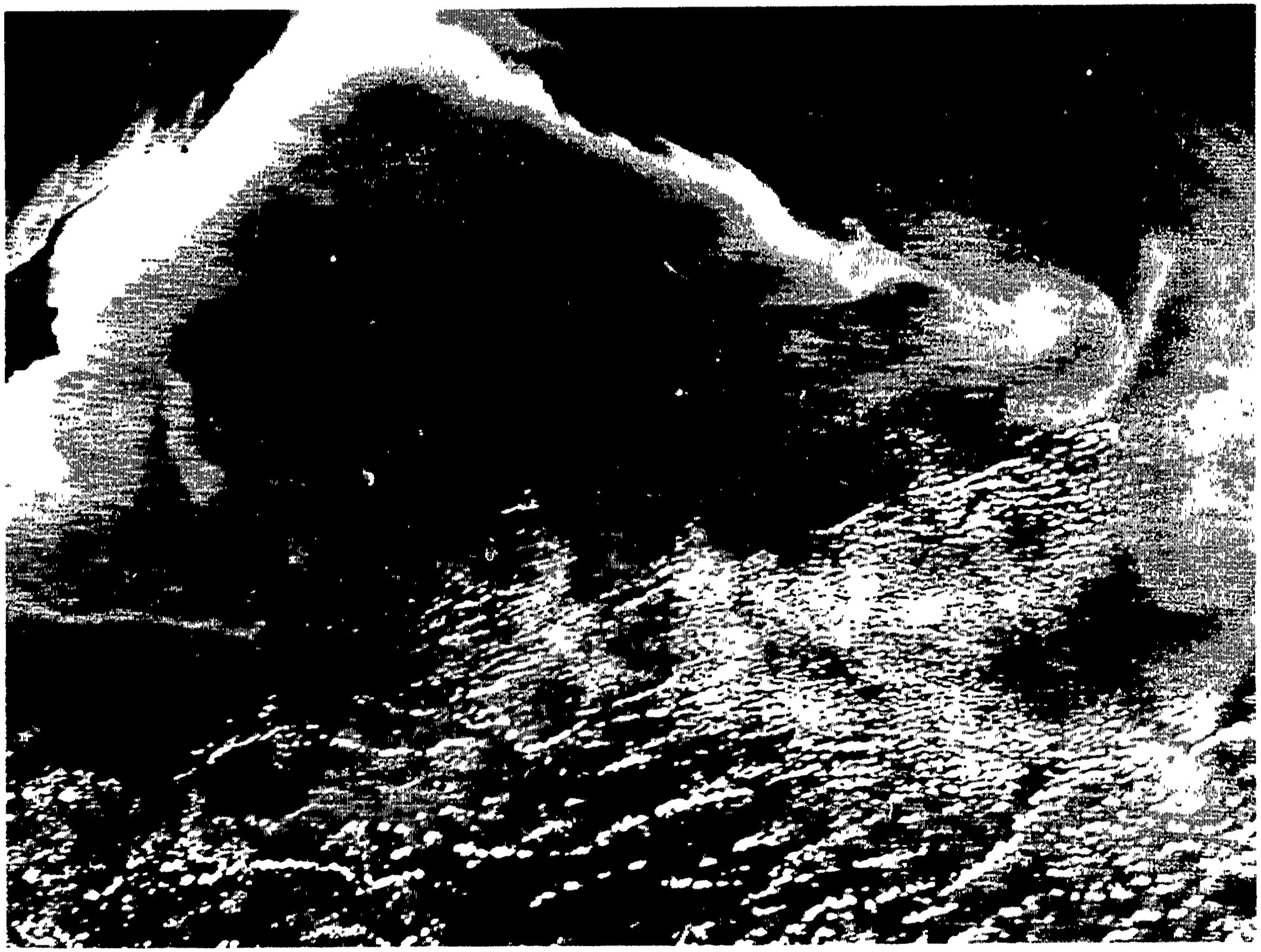

Figure 9. Enhanced Infrared Image of Area Off Arabian Coast.

This view was taken on 30 May 1980 of the area east of the point of land entitled Ra's al Hadd. Cold upwelling along the Arabian Coast, as well as the extended plume, is apparent by the lighter grey shades in this image.

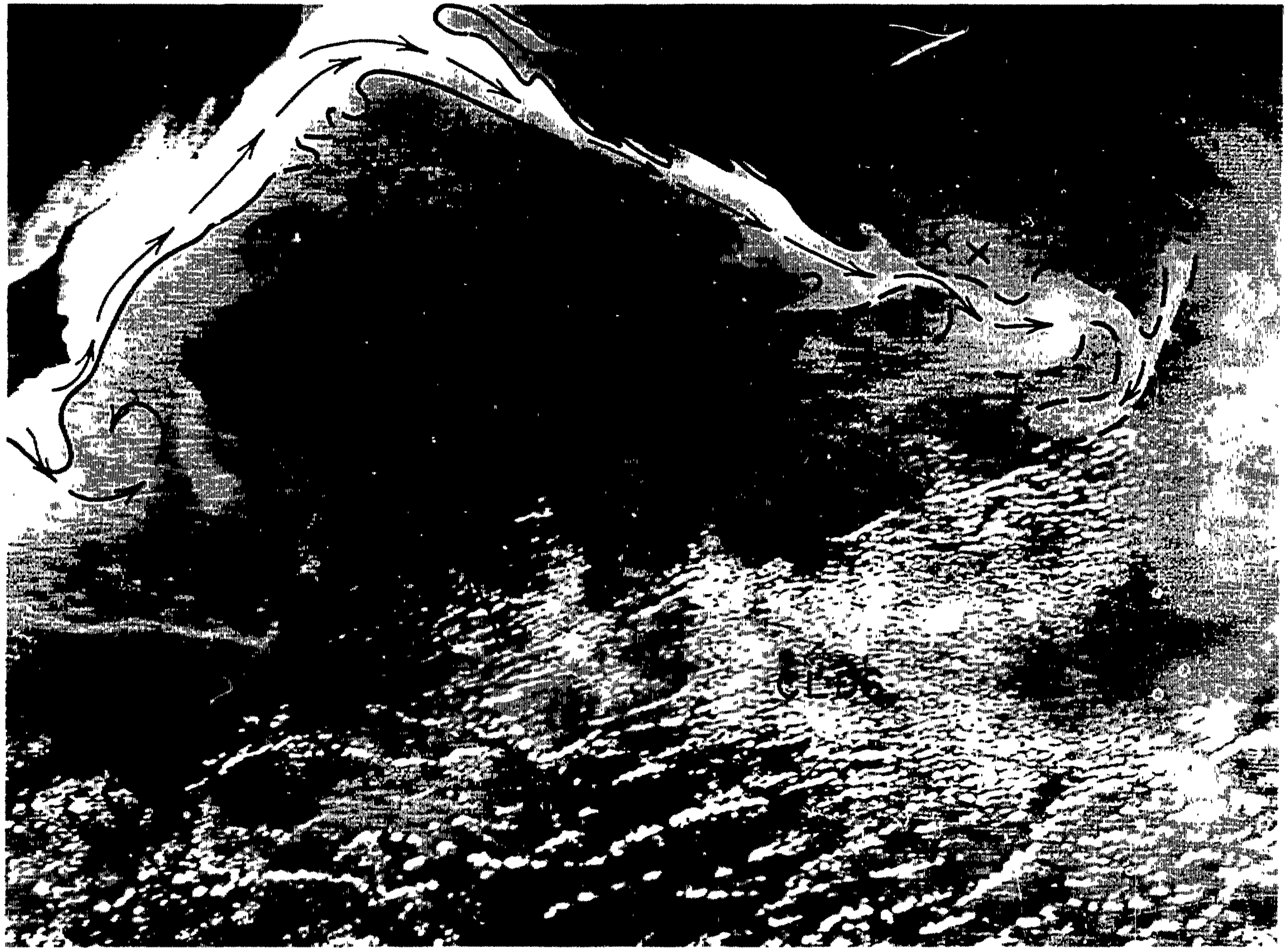

Figure 10. Overlay with Interpretation for Figure 9.

This overlay (photographed on Figure 9) was prepared to show the interpretive, instantaneous flow pattern of a cold upwelling plume which extends east southeast for more than 100 nautical miles.

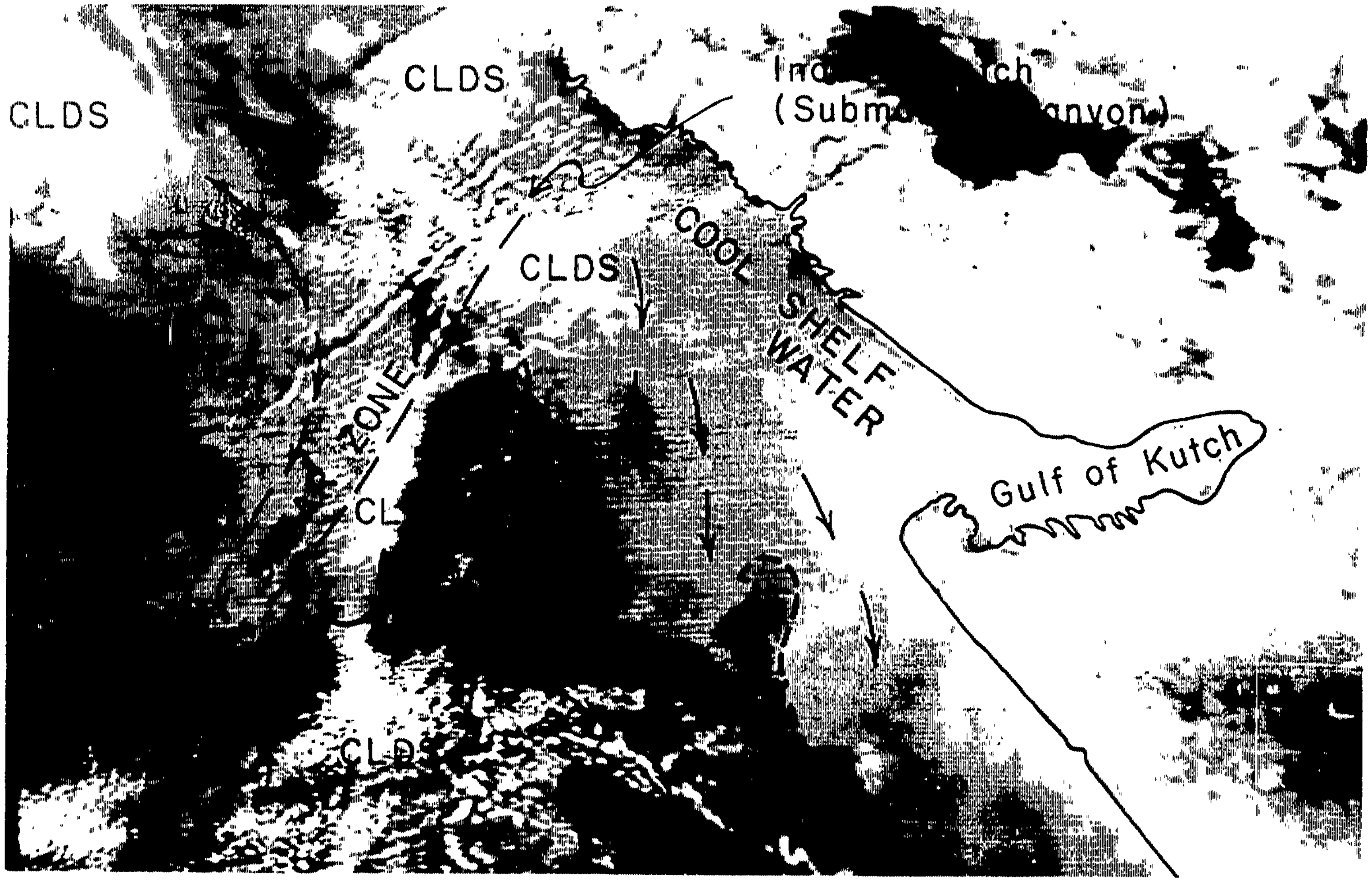

Figure 11. Enhanced Infrared Image of Arabian Sea Area Southwest of Karachi, 18 March 1980.

This area, in the northeast corner of the Arabian Sea, appears to have lines of small vortices along shear lines that lie over, and south of, a large submarine canyon, entitled the Indus Swatch. Warm water is slowly transported northward along the edge of the shelf. Cool water persists on the shelf and a southward flow of cool water appears farther offshore. In Figures 11, 12, and 13, the overlay was photographed with the image to indicate the interpretations.

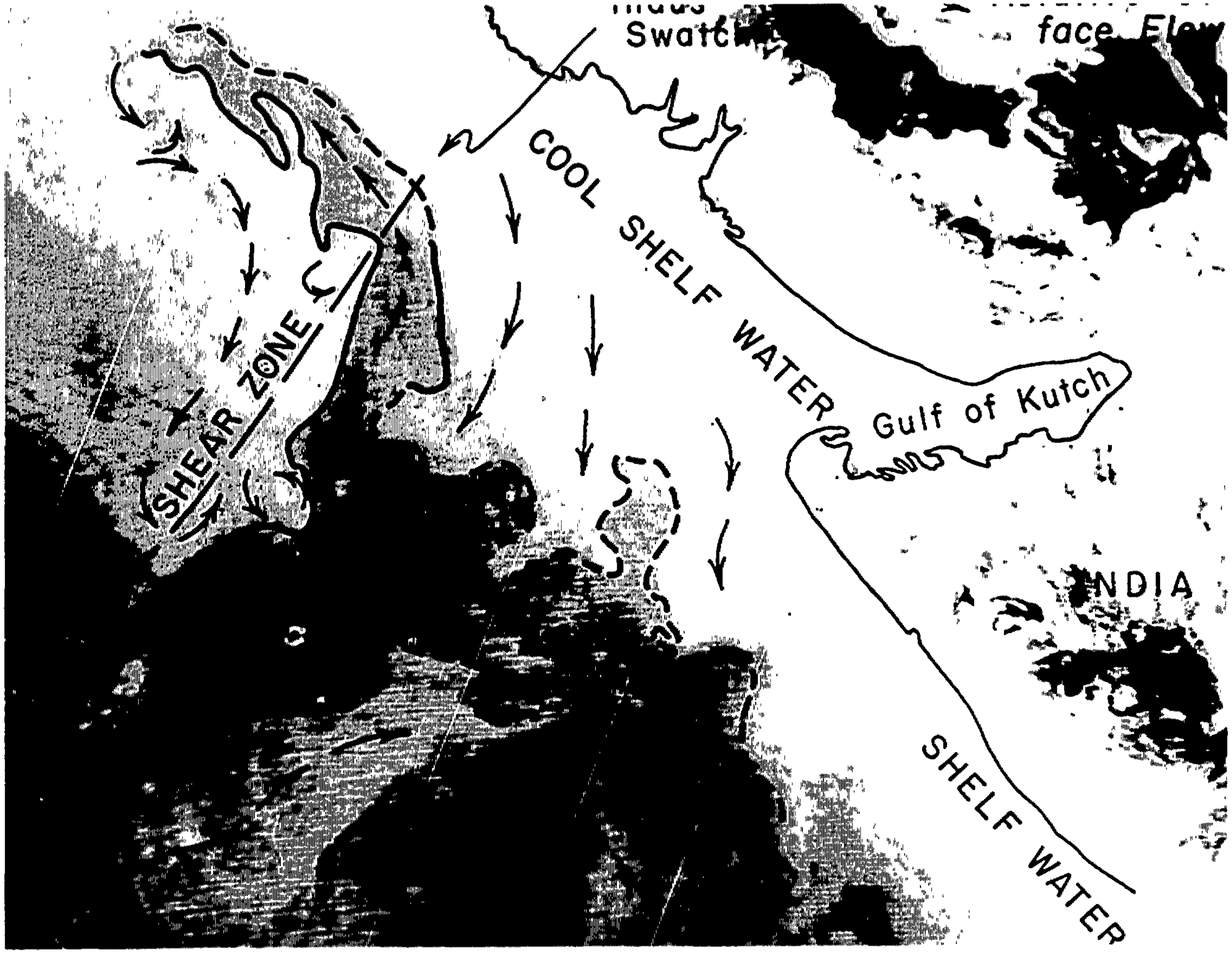

Figure 12. Enhanced Infrared Image of Arabian Sea Area Southwest of Karachi, 19 March 1980.

This view follows that of Figure 11, and shows the shear line and small vortices.

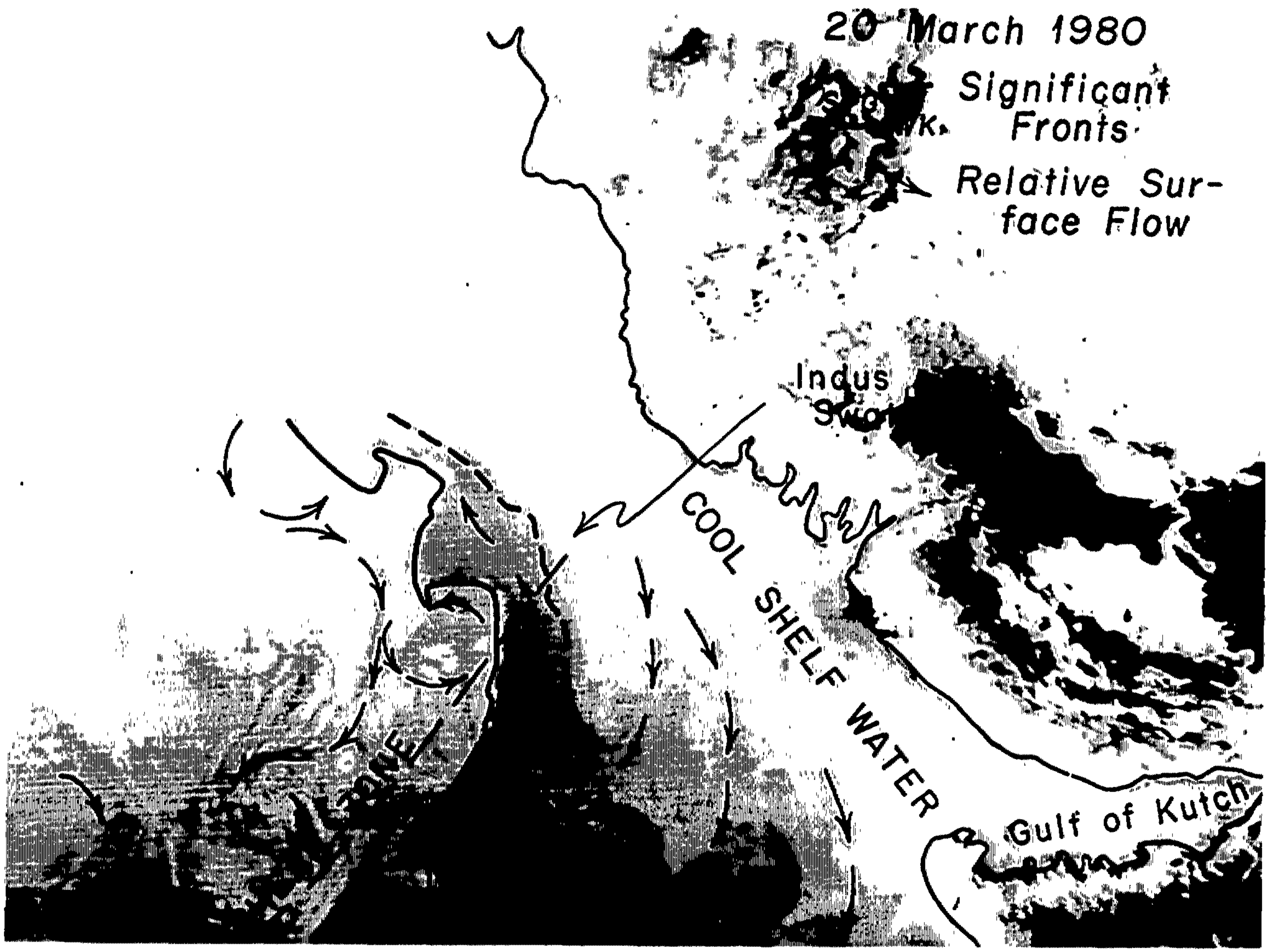

Figure 13. Enhanced Infrared Image of Arabian Sea Area Southwest of Karachi, 20 March 1980.

This image follows that of Figures 11 and 12, and again shows the shear lines and small vortices. This three-day sequence shows some change in the evolution of the features.