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Application of Satellite Infrared Data to Analysis of Ocean Frontal Movements and Water Mass Interactions off the Northeastern United States

by

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1. INTRODUCTION

I have been asked to address a large and important subject. It deals with the efforts of several oceanographers over a period of several years to use data from a major new technology to analyze variability in circulation and water mass distributions in the Northwest Atlantic from off Nova Scotia to Virginia, with a view toward increasing understanding of the influence of this variability on the fishing grounds and fishery resources. Such analysis has been practical on a routine, year-round basis only since late 1973, when high resolution (1 km) infrared radiometers were deployed in polar orbiting NOAA satellites. Infrared has continued to be the only operationally available data from environmental satellites which can be used to analyze ocean circulation and water mass distributions. The Northwest Atlantic is one of the most favorable areas in the World Ocean for such analysis, because of its strong sea surface thermal contrasts associated with the Gulf Stream. These contrasts may be detected by satellites even when there is significant reduction in atmospheric transparency to infrared radiation from the sea surface. The term thermal signifies that the analyses have not been based on numerical temperature data, but rather on:

1. Charts of the surface positions of thermal fronts prepared by the NOAA National Earth Satellite Service (Fig. 1) and, until 1979, more detailed charts by the U.S. Naval Oceanographic Office (Fig. 4). In these charts, the positions of permanent fronts and prominent transient fronts are composited to Mercator projection from the clear-sky portions of thermal infrared imagery over periods of a few days to a week.

2. Thermal infrared imagery from NOAA polar orbiting and geostationary satellites. Processed in shades of gray, the imagery reveals only the relative strength of thermal gradients, with no correction for variations in atmospheric interference. Image processing, however, is adjusted for the annual sea-surface temperature cycle by seasonal or more frequent changes in the enhancement curves used to produce the gray scales.

To recognize the importance of satellite infrared data to fishery science in the Northwest Atlantic, two fundamental oceanographic characteristics of this region require consideration. The first is that the continental shelf, where the fishery resources are largely concentrated, is a relatively low energy area bounded offshore by the far more dynamic conditions in the oceanic regime of the slope water and Gulf Stream. The second consideration is that prior to the orbiting of second generation environmental satellites seven years ago, the influence of oceanic conditions on the fishing grounds was essentially a hidden variable. In contrast, routine data on the astronomical influence of tide and on meteorological influences, such as atmospheric pressure, wind, air temperature, and coastal runoff have been available and studied for many years. Satellite infrared radiometers now provide a basis for almost continuous assessment of physical variability in the oceanic regime, and a foundation for investigating the influence of this variability on the continental shelf fishing grounds.

Although the satellite radiometer only measures infrared radiation from the surface film of the ocean, the resulting data are providing a new level of understanding of circulation in the Northwest Atlantic, not only at the surface, but also beneath the surface to many hundreds of meters depth. The basis for this understanding is the unique capability of the satellites to measure the movements of the permanent ocean fronts in detail over vast areas of the ocean. These fronts, whose changes in position are synonymous with changes in circulation pattern, extend to the bottom or to great depth, and the subsurface configurations of those in the Northwest Atlantic are fairly well understood from shipboard observations. Consequently, the locations of permanent fronts in this region at depth can be estimated from their location at the surface with sufficient accuracy for many oceanographic purposes. Furthermore, errors in estimating the location of these fronts beneath the surface, tend to be outweighed by much larger horizontal movements of the fronts in their entirety, throughout the water column.

It should also be recognized that the satellite infrared data provide an integrated picture of how the permanent fronts move relative to one another and how the water masses interact through the major cross frontal exchange process of Gulf Stream ring production, and through the effects of the energetic rings, themselves, on the waters around them. In this context, it has become clear from the infrared data that warm core Gulf Stream rings warrant particular attention by fishery oceanographers, because these features may be the principal mechanism which transfers Gulf Stream water and motion (kinetic energy) into the vicinity of the continental shelf and slope where the preponderance of the fishery resources are concentrated.

Section 2 of this report provides, as background information, a summary of the ways in which satellite infrared data have been used in research in the Atlantic Environmental Group. Although a full summary of the results of this research is beyond the scope of the present report, it is nonetheless impractical to focus discussion on remote sensing applications in the Northwest Atlantic except in terms of the oceanographic conditions of that region. Therefore, salient features of the ocean regime beyond the continental shelf are briefly described in Section 3. Included in the description are some examples of the results of research carried out in the Atlantic Environmental Group with satellite infrared data.

The remaining sections, 4 and 5, consider the applicability and limitations of satellite infrared data in research on ocean frontal movements and water mass interactions, as well as possibilities for improvement in the use of satellite remote sensing.

2. USE OF SATELLITE INFRARED DATA IN OCEANOGRAPHIC RESEARCH CONDUCTED IN THE ATLANTIC ENVIRONMENTAL GROUP

Two types of analysis have been carried out in the Atlantic Environmental Group annually since 1974 principally with satellite infrared data:

1. Variations in the position of the shelf-slope water front from Georges Bank to Cape Romain, South Carolina. These analyses were based on the Satellite Derived Gulf Stream Analysis charts issued weekly by tOe NOAA National Environmental Satellite Service until 1980, and subsequently on the Oceanographic Analysis charts (Fig. 1) issued each Monday, Wednesday, and Friday since May 1980, by the NOAA National Weather Service and National Earth Satellite Service. Surface positions of the front have been recorded from the charts by measuring its distance offshore or onshore of the 100 fm (187 m) isobath along several standard bearing lines (Figs. 2, 3). The influence of Gulf Stream warm core rings on the position of the front has also been evaluated on the basis of these charts. The most recently published of these analyses (for 1979) is by Hilland (1981).

2. Anticyclonic warm core Gulf Stream rings (eddies) off the northeast United States and Canadian Scotian Shelf. These analyses were based from January 1974 to May 1978 on the Experimental Ocean Frontal Analysis charts, issued weekly by the U.S. Naval Oceanographic Office (Fig. 4); from June 1978 to May 1980 on the Satellite Derived Gulf Stream Analysis, issued weekly by the NOAA National Environmental Satellite Service; and since May 1980 on the Oceanographic Analysis charts issued each Monday, Wednesday, and Friday by the NOAA National Weather Service and National Earth Satellite Service (Fig. 1). Infrared imagery from NOAA geostationary satellites has been used since 1976, and from NOAA polar orbiting satellites since 1978, to re-evaluate, modify, and add to warm core ring positions on the charts. The movement of each ring which occurred west of 60°W longitude has been tracked (Figs. 5, 6) and its origin, periodic interactions with shelf water and the Gulf Stream, and ultimate destruction has been described, so far as possible with infrared imagery and other data available. The most recently published of these reports (for 1979) is by Fitzgerald and Chamberlin (1981). In each of the above described series of reports correlations have been included with available shipboard water column observations.

Another series of annual analyses has been on temperature structure across the continental shelf and slope south of New England. Although principally based on shipboard observations, these analyses have routinely included information from satellite infrared data to correlate the influence of warm core rings on bottom temperature. The most recently published of these analyses (for 1979) is by Crist and Chamberlin (1981).

Satellite infrared data have been extensively used in investigation of the effect of oceanographic conditions on waste dispersal in the 106 Mile Dumpsite located southeast of Hudson Canyon. Satellite data have been used in conjunction with shipboard observations to estimate variability in the relative volume of shelf, slope, and warm core ring water within the Site, and to describe the configurations, movements, and entrainment effects of the rings. Infrared imagery and frontal analysis charts have been useful in determining the relation to rings of current measurements from drifting buoys tracked with satellites and shore-based radio-direction instruments. (A recent report is by Bisagni (MS).

Multiple year "climatological" research is also now in progress, based on data derived from the satellite infrared imagery for the period since 1974. In one project statistics are being developed on the origins, rates of movement, and other characteristics of warm core rings. Some preliminary results are included in the following section of this report. Another project involves time-dependent correlations of the surface areas of the shelf water, slope water and warm core rings off the northeast coast of the United States.

3. WATER MASSES, GULF STREAM MEANDERS AND RINGS IN THE NORTHWEST ATLANTIC

North of Cape Hatteras the Gulf Stream turns northeast into deep water and tends to meander with increasing amplitude downstream. The deep ocean between the Stream and the continental slope is occupied by the slope water mass which is intermediate in properties between the colder, less saline shelf water mass on its shoreward side and the warmer, more saline Gulf Stream offshore (Fig. 7B). A permanent steep temperature and salinity gradient, the shelf-slope water front which separates shelf and slope water, makes contact with the bottom on the outer continental shelf and reaches the surface some miles farther offshore. (During parts of the summer, temperature contrast across this front may disappear near the surface). During the spring and summer of 1978, this front was far offshore of its normal position at the surface (Flagg and Beardsley, 1978) off Georges Bank and the Middle Atlantic coast (Fig. 3).

Meanders reaching amplitudes of around 150 km and greater often detach from the Stream and close into rotating masses of water called Gulf Stream rings or eddies (Fig. 8). Warm core rings form in the Slope Water region by detachment of meanders on the left (shoreward) side of the Stream, and cold core rings form in the Sargasso Sea by detachment of meanders from the right side (Fig. 8). The rotation of warm core rings is clockwise (anticyclonic) at measured peripheral speeds from as low as 30-50 cm/sec (Saunders, 1971) to as fast as 140 cm/sec (Cheney, 1978). The rings have a warm core because they enclose Sargasso water that has crossed the Gulf Stream within the originating meander (Fig. 8). Greatest in area near the sea surface (Fig. 7A), rings, when newly formed, have ranged in diameter from about 150 to 230 km, and may reach depths of over 2000 m. Unlike Gulf Stream meanders which move slowly in the direction of the Stream, warm core rings typically move in a direction opposite to that of the Stream, at average speeds up to about 15 cm/sec over periods of several days. However, they often halt or move in irregular directions for days or even several weeks (Fig. 5). Because most warm core rings seen off New England and the Middle Atlantic coast form southeast of Georges Bank (Fig. 9), where Gulf Stream meanders often reach high amplitude, they are often destroyed near their place of origin (Fig. 10) within a few weeks or months after formation, by encountering one of these meanders. Those which escape destruction and reach the longitude of Cape Cod, usually persist for several more months until eventually resorbed by the Gulf Stream at about the latitude of Virginia (Fig. 10), where the Stream runs close to the continental slope. The frequency distribution of ring longevity (Fig. 11) provides more direct evidence that warm core rings tend to be either short- or long-lived. The production rate of rings occurring in the Slope Water west of 60°W longitude during the past seven years has varied from six in 1974 (unplublished data) to eleven in 1979 (Fitzgerald and Chamberlin, 1981). During these years, variation in the number of rings simultaneously present has ranged from eight during a period of a week or two in early May 1977 (Mizenko and Chamberlin, 1979) to none during a six-week period from March to mid-April, 1978 (Celone and Chamberlin, 1980).

Cold core rings form in the Sargasso Sea from meanders on the right (offshore) side of the Gulf Stream (Fig. 8). Opposite in structure to warm core rings, they rotate counter-clockwise, and contain a core of the relatively cold Slope Water (Fig. 7A). Although studied more than warm core rings by oceanographers cold core rings are not at present of direct importance in fishery research.

4. APPLICABILITY OF SATELLITE INFRARED DATA TO OCEANOGRAPHIC INVESTIGATION IN THE NORTHWEST ATLANTIC

The applicability of satellite infrared data to oceanographic investigation is partly process dependent.

Permanent Fronts and Boundaries of Warm Core Rings: At the present level of technical development, the most informative application of satellite infrared data to oceanographic investigation in the Northwest Atlantic is in analyses of the movements of the permanent fronts which separate the surface water masses (shelf, slope, Gulf Stream, and Sargasso Sea) and the quasi-permanent boundaries of Gulf Stream warm core rings. Because the structure of these fronts at depth are fairly well understood by oceanographers, their surface positions are useful indices of their positions throughout the water column. Furthermore, the positions of these fronts at the surface can be measured and charted more frequently and in more detail with satellite infrared data than is possible with any other data available at present.

Satellite infrared data reveal the various permanent fronts in the Northwest Atlantic with varying consistency. The Gulf Stream is apparently always visible in clear sky imagery, because its warm surface core water, of tropical origin, seems never to lose thermal contrast with the adjacent slope and Sargasso Sea waters.

Warm core rings are less consistently visible in infrared imagery. Their sizes and locations are poorly indicated when their surface thermal patterns become temporarily distorted. Some of these distortions result from rings being overridden by entrained Gulf Stream, Slope, or Shelf water, and others are possibly caused by winter winds chilling rings at the surface. If subsequent imagery is not distorted, however, the problem can be dealt with to a degree by interpolation.

Satellite infrared imagery often fails to reveal old warm core rings, because they tend to lose surface thermal contrast with the surrounding slope water. When this occurs, however, the sizes and locations of rings can often be estimated from encircling bands of entrained shelf or Gulf Stream water. Off the Middle Atlantic coast of the United States during the summer, rings are particularly likely to be invisible in infrared imagery, because surface thermal contrasts often disappear between rings, slope water, and shelf water. In this circumstance, rings can be located only when they are entraining Gulf Stream water. Such entrainment, however, is not usual, because the great majority of the rings in this region are old, reduced in size, and remian close to the continental slope where they are not in proximity to the Stream.

The shelf-slope water front can be located even less consistently than warm core rings, because, as mentioned in the previous paragraph, surface thermal contrast frequently disappears across it during much of the summer and early fall.

Transient Fronts and Water Mass Interactions: Satellite infrared data are less effective and less informative for analysis of short period transient fronts than for analysis of permanent or long period fronts. This contrast may be illustrated by comparing analysis of shelf water (or Gulf Stream) entrainment by a warm core ring with analysis of the movements of the ring itself. Following a period of several days to a few weeks, when a ring is "hidden" from the satellite radiometer by clouds, interpolations can usually be made of the ring's positions and surface area during that period, based on mear certainty that the ring continued to exist during that period. Frontal patterns visible in the neighborhood of the ring may permit more accurate estimates of the positions than by simple interpolation. In contrast, neither the continuity nor duration of surface entrainment features can be estimated during such periods because duration of the entrainment process may be as brief as a few days.

Satellite infrared is less informative about transient fronts than permanent fronts, because the processes evidenced by the fronts are less well understood than those associated with permanent fronts. For example, the primary information on entrainment, sought by oceanographers, is an estimate of volume transport. Satellite infrared data only provide an estimate of the surface area and shape of the entrainment, and an indication of the direction of flow which led to that configuration. To estimate volume transport, additional data are needed, usually from shipboard observations, on the volume of the entrained water and its velocity.

Satellite infrared data, despite their limitations, are the most geographically comprehensive and frequent source of information on transient fronts, both those associated with processes within water masses and those associated with exchange between water masses. (Processes within the shelf water mass, although important to fishery oceanography in the Northwest Atlantic are not considered in this report). In analysis of entrainment by rings (see previous paragraph) the infrared data may be invaluable for guiding not only shipboard observations, but also interpolations amongst data during the subsequent analysis.

The intermittency of surface entrainment of shelf water (also of Gulf Stream water) by warm core rings, as evidenced in infrared data, is certainly a significant characteristic of the process and one that has apparently not been investigated. Entrainment must depend, of course, on a ring being within some minimum distance from the shelf-slope water front. Proximity of the ring to shelf water, however, is not a sufficient condition for entrainment. Shelf water entrainment by rings renaiming close to the shelf-slope water front is intermittent, with periods varying from a few days to a few weeks.

Ring-associated injection of warm water onto the outer continental shelf is an example of a water mass exchange process for which satellite infrared data provide useful, although only indirect information. These injections do not seem to be detectable in satellite infrared data, but are often seen in vertical temperature sections (see, for example, Crist and Chamberlin, 1979), where they are predominantly near the bottom. Neverless, these data could be a valuable guide during shipboard investigations of the process, by revealing when and where injections may be taking place.

Need for Additional Analyses: Optimum use of satellite infrared data for investigating physical oceanographic variability in the Northwest Atlantic requires a larger range of frontal analyses than has yet been attempted. Analyses at higher derivative levels are now appropriate. For example, rates and magnitudes of frontal movements of fronts and rings correlated with one another. The analyses should encompass the entire region, offshore to beyond the Gulf Stream. In view of the continuity of water masses and tendency of warm core rings to move throughout the length of the slope water area, the analyses should encompass the entire region from the shelf to beyond the Gulf Stream. It may not be practical, however, to include the waters beyond the Scotian Shelf to the east, because of greater frequency of cloud cover.

5. POSSIBLE IMPROVEMENTS IN USE OF SATELLITE REMOTE SENSING FOR RESEARCH ON OCEAN FRONTS

Improvements can be made in the use of satellite remote sensing for ocean frontal analyses through:

1. more efficient use of the infrared data presently available from NOAA operational environmental satellites

2. employment of new satellite technology to overcome inherent limitations of infrared data

In both cases, regional remote sensing facilities will be required for rapid data acquisition and specialized data processing appropriate to the particular oceanographic conditions of the Northwest Atlantic. To meet this requirement, an ocean remote sensing facility is being developed in Narragansett, Rhode Island as a cooperative endeavor of the University of Rhode Island and the National Marine Fisheries Service. This facility is to be affiliated with a regional organization, the Northeast Area Remote Sensing System.

Improvements in Use of Infrared Data: Listed below are possible improvements in the use of satellite infrared data:

1. Image processing: Special processing of individual images to reveal the full range of surface thermal gradients that are recorded in the radiometer data, or to reveal local gradients in more detail.

2. Correction of infrared data to sea surface temperature values:

   -- Polar orbiting satellites (TIROS-N series). Sea surface temperature values with a spatial resolution of 1.1 km and an error of about 0.5°C can apparently be computed from the advanced very high resolution radiometer (AVHRR) data. This is done through comparison of readings at wave lengths of 3.7, 10.9, and 12 micrometers in the thermal infrared band, to correct for atmospheric interference (Deschamps and Phulin, 1980; Kidwell, 1981).

   -- Geostationary satellites (GOES). Time compositing of infrared data from geostationary satellites can be used to chart sea surface temperature with more complete geographical coverage than is possible with data from the TIROS-N satellites, although with lower resolution (8 km) and less accuracy. The technique developed by Waters and Baig (1977) takes advantage of the high rate of the data collection by the geostationary satellites (every 30 minutes, compared to every 12 hours by the polar orbiting satellites) and the fact that cloud movements "expose" different areas of the sea surface to the satellite's radiometer during the progress of a day. Computer comparison of successive sets of data, pixel by pixel, with selection of the warmest value, decreases the effect of atmospheric interference. The resulting data can be displayed in digital printouts or as imagery in gray scales. The compositing routine has been under development in the NOAA National Environmental Satellite Service since 1977, with the objective of establishing an operational sea surface temperature mapping service for the waters off the Atlantic and Gulf coasts. A fixed selection of data from a six-hour period each day has been used to produce experimental products. With modification, the routine could take full advantage of the satellite's high frequency, round-the-clock, data collection, to achieve maximum clear sky coverage for each 24 hours.

3. Frontal analysis charts: The detail and geographical accuracy could be improved and the efforts of the analyst made more efficient by providing each of the improvements listed above, and in addition, facilities for automated reformatting of frontal positions from imagery to a standard map projection.

Improvement through Use of New Satellite Remote Sensing Technology: Consideration is restricted here to two kinds of remote sensing technology: synthetic aperture radar (SAR) and the coastal zone color scanner (CZCS). Each provides data which can be processed as imagery and can partly compensate for inherent limitations in frontal analyses based on thermal infrared data.

1. The synthetic aperture radar (SAR) was successfully orbited in the short-lived Seasat 1, a NASA research satellite. It provided "extremely high resolution (25 m) images of wave patterns as modified by currents, shoaling, internal waves, and oil spills." (McClain, 1980). A few of these images have been published (for example, see Behie and Cornillon, 1981). These indicate that SAR could be a powerful instrument for detecting ocean fronts. Lichy et al. (1981), through comparison with AVHRR thermal infrared imagery in which a Gulf Stream warm core ring is visible found that SAR detected this ring during all six passes made over it by Seasat 1 during September-October 1978. "Characterized by concentric curvilinear or arcuate bands", the ring configurations in SAR were smaller than in infrared, but the ring positions were in close agreement (Fig. 12). (Entrained shelf water encircling the ring does not seem detectable in this SAR imagery, although prominent in the infrared). The virtually all-weather capability of SAR gives it some distinct advantages over infrared for analysis of ocean frontal movements.

2. The coastal zone color scanner (CZCS), successfully operated for over two years in Nimbus 7, a NASA research satellite, was designed principally to measure ocean color variations in four spectral bands. In offshore waters the principal color variations detectable in CZCS data apparently relate to concentrations of chlorophyll a in phytoplankton. Detection of ocean fronts with CZCS, or other multispectral ocean color scanners, will presumably depend, therefore, on differences in chlorophyll concentration between water masses. Peter Cornillon, of the University of Rhode Island, has processed a limited qualtity of CZCS imagery for the Northwest Atlantic. He was able to locate a warm core Gulf Stream ring in imagery for both visible and thermal infrared wave lengths (personal communication). Investigation is needed on the possibility of using CZCS to locate ocean fronts and warm core rings when sea surface thermal contrasts are negligible.

6. SUMMARY

1. Measurements of thermal infrared radiation from the sea surface have been the basic remote sensing data for detecting movements of ocean fronts and water mass interactions since 1973 when second generation NOAA operational environmental satellites were placed in orbit. The unique capability of these satellites to provide frequent, detailed data on these movements and exchanges has led

to a new level of understanding of physical oceanographic variability in the Northwest Atlantic, especially in the dynamic deep ocean regime adjacent to the continental shelf and slope, where the preponderance of the fishery resources are concentrated.

2. Annual analyses since 1974 of the movements of the shelf-slope water front and Gulf Stream warm core rings off the northeast coast have indicated the direct use potential of the satellite infrared data for oceanographic research, but a broader range of analyses are needed to realize the full potential (e.g., movements of the Gulf Stream and correlations of the movements of fronts relative to one another).

3. Satellite infrared data are more effective and informative for analyses of the permanent and long period fronts than for analyses of transient fronts such as those associated with entrainment of shelf water or Gulf Stream water by warm core rings. The infrared data are invaluable, however, as a guide to sea-going investigations of the processes with which both classes of fronts are associated.

4. Improvements can be made in the use of satellite remote sensing for analysis of ocean frontal movements and water mass interactions through

    -- more efficient use of the infrared data presently available from NOAA environmental satellites, and

    -- operational use of new satellite environmental sensors to overcome inherent limitations of infrared sensors.

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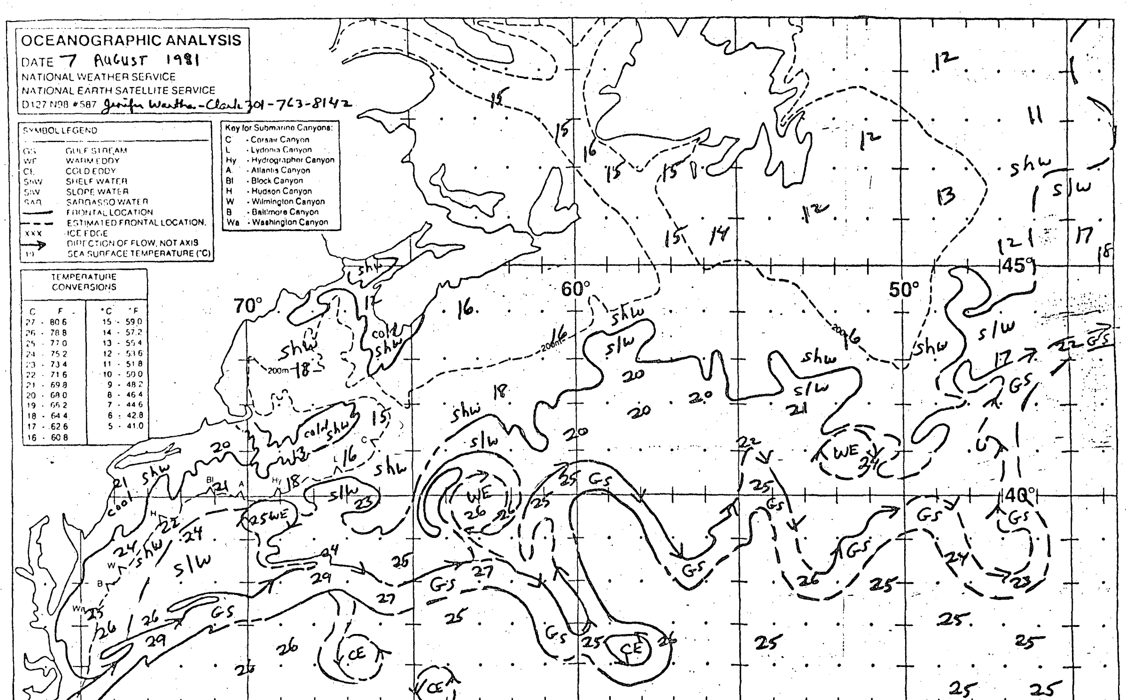

Figure 1. Oceanographer Analysis for 7 August 1981. NOAA National Weather Service/National Earth Satellite Service.

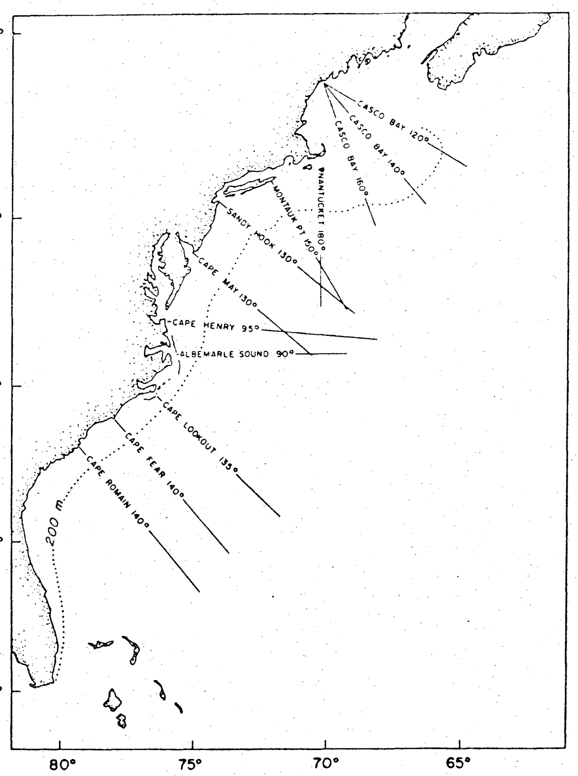

Figure 2. Reference points and bearing lines used to portray the variation of the position of the shelf-slope water front relative to the 200 m isobath (After Hilland, 1981).

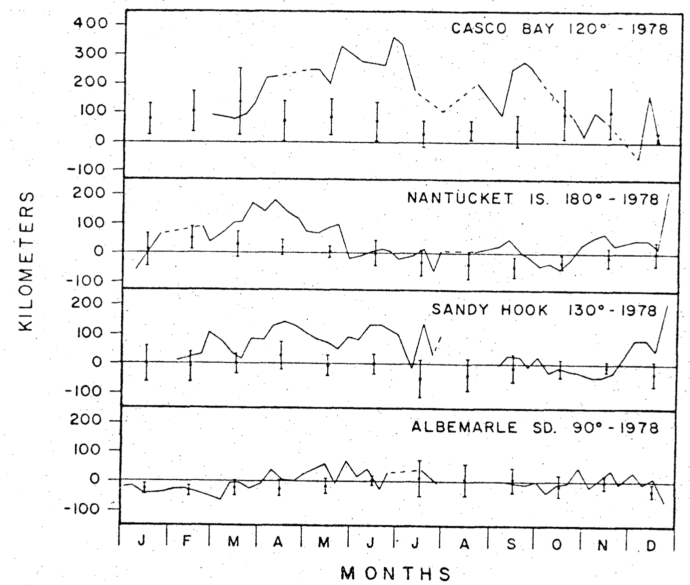

Figure 3. Shelf water frontal positions in 1978 relative to the 200-m isobath (positive is seaward) on selected bearing lines. Dotted lines indicate gaps in the data of 2 to 4 weeks. Breaks in lines indicate gaps greater than a month. Mean monthly positions of the front are shown as dots with the vertical lines representing 2 standard deviations around the means for the base period June 1973 to December 1977. (After Hilland and Armstrong, 1980).

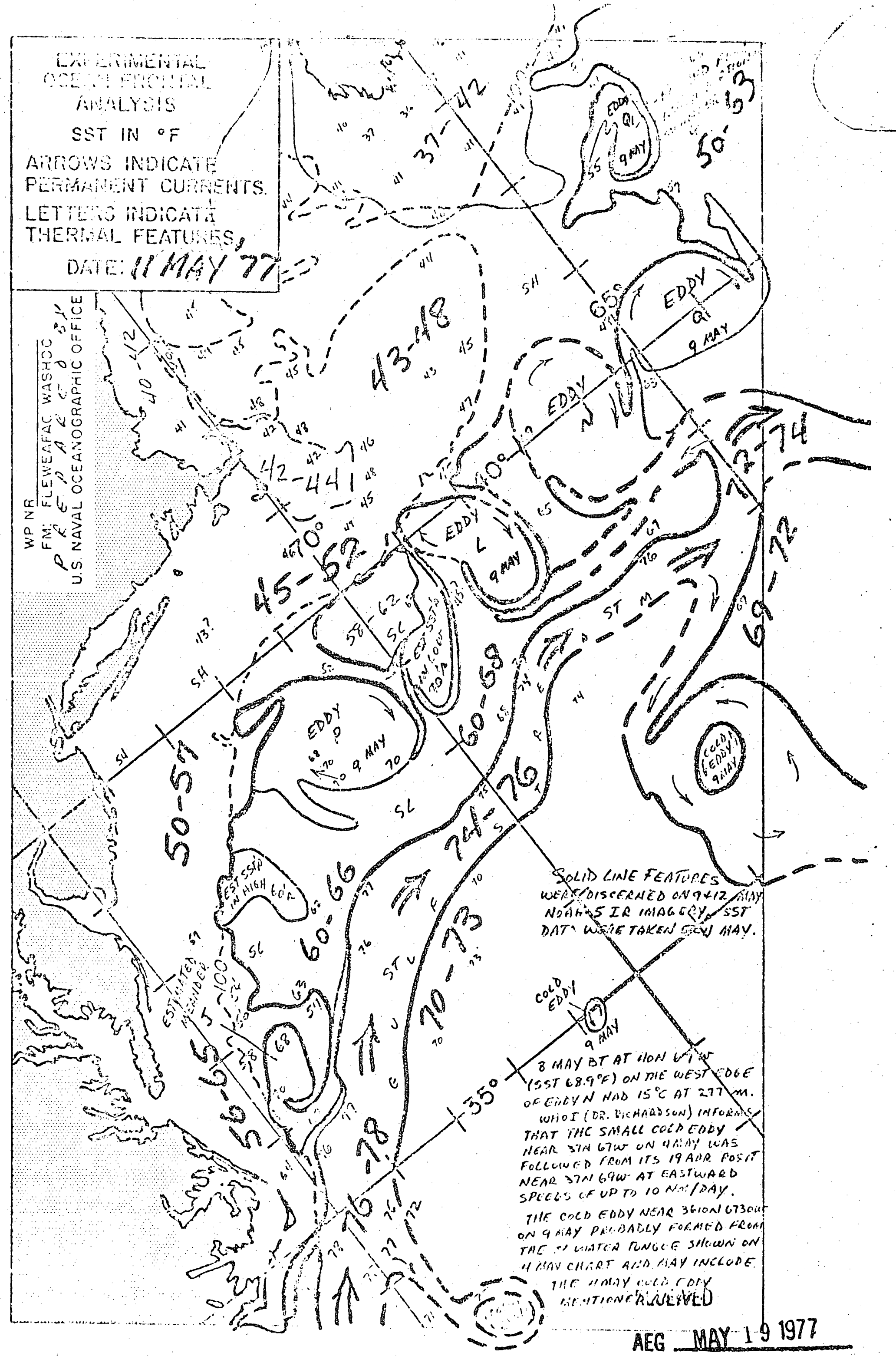

Figure 4. Experimental Ocean Frontal Analysis for 11 May 1977, U.S. Naval Oceanographic Office.

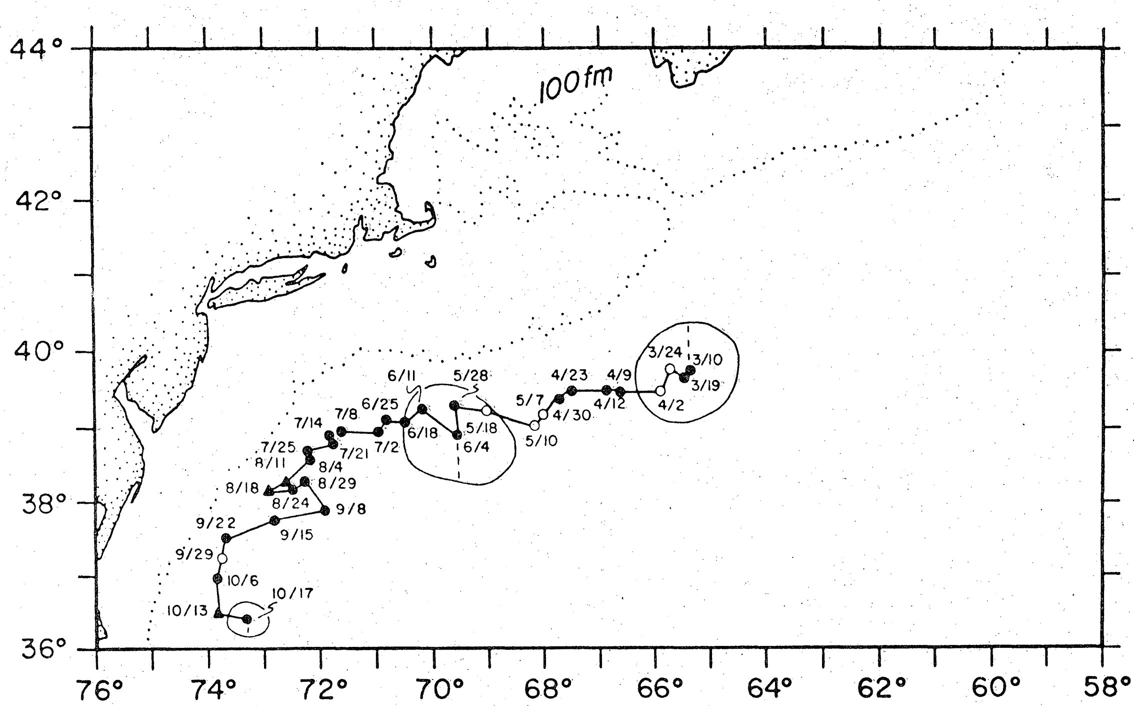

Figure 5. Trackline for Gulf Stream warm core ring 80-A during 1980. Dots are estimated center positions on the indicated dates. Ring boundaries interpreted from NWS/NESS oceanographic Analysis charts and satellite infrared imagery are included for selected dates (After Fitzgerald and Chamberlin, MS).

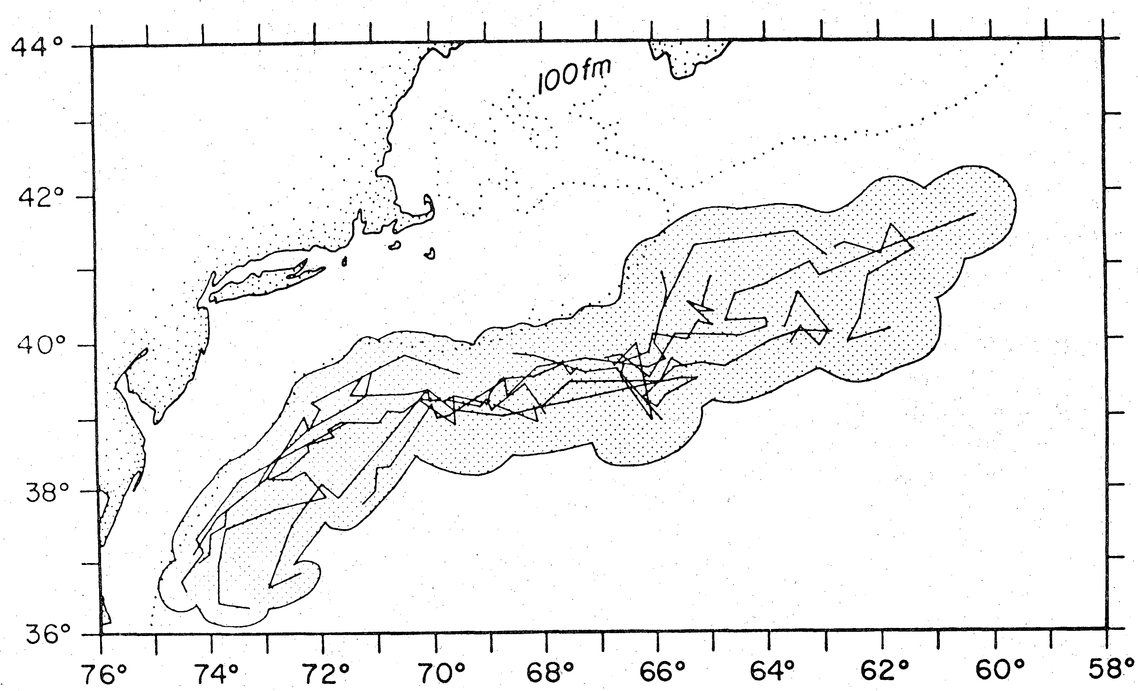

Figure 6. Composite tracklines of Gulf Stream warm core rings and an envelope of composited ring surface boundaries during 1980 (After Fitzgerald and Chamberlin, MS).

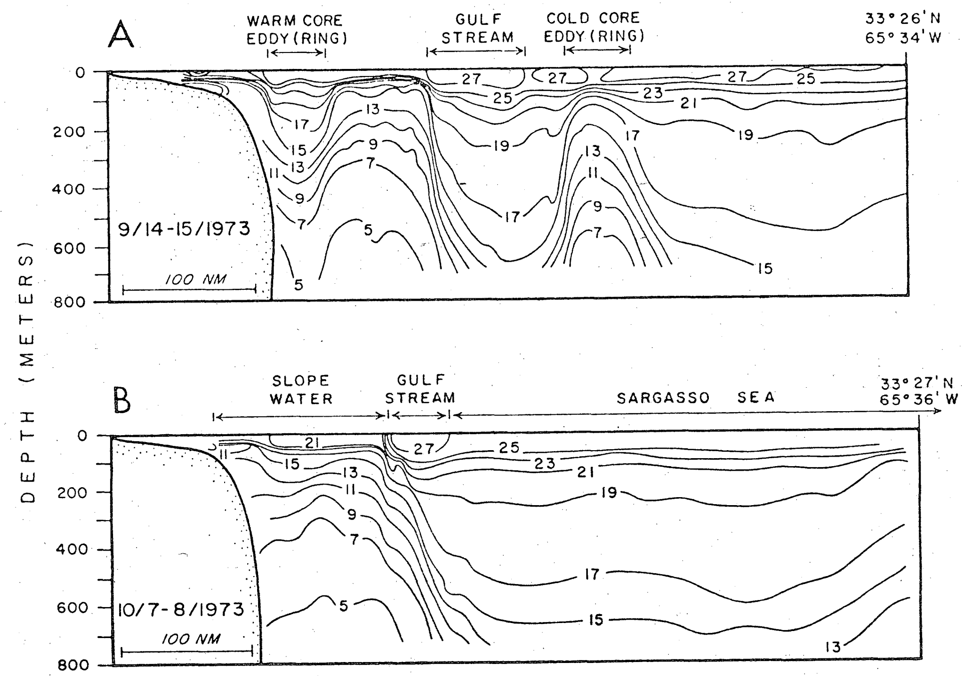

Figure 7. Vertical temperature sections from off New York City toward Bermuda. Lines of equal temperature are drawn at intervals of 2°C: A. Illustration of the structure of a warm core ring (in the slope water region) and a cold core ring (in the Sargasso Sea). B. Illustration of temperature structure when no eddies are present. (From Gulf Stream Monthly Summary, July 1974, U.S. Naval Oceanographic Office.)

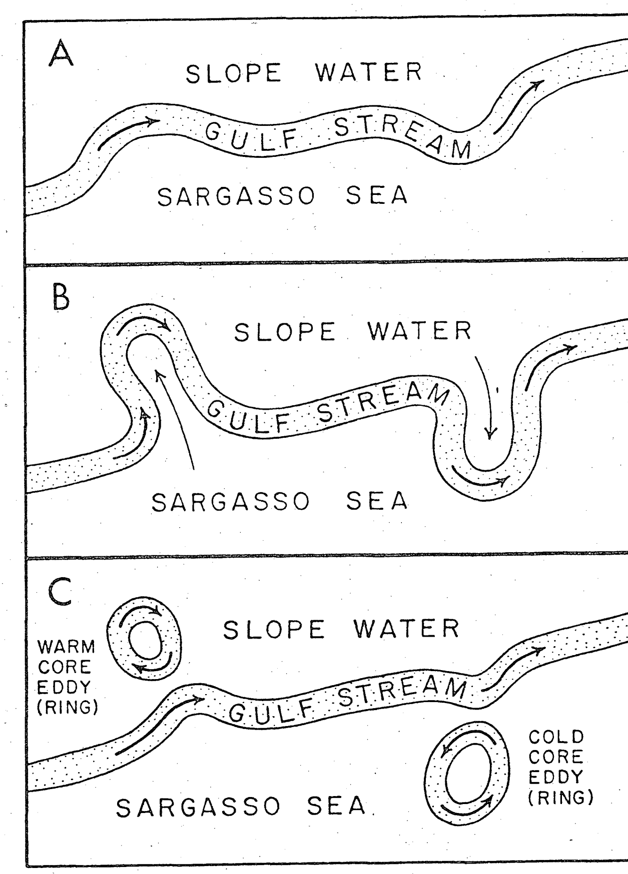

Figure 8. Diagrams of Gulf Stream ring formation. Warm and cold core rings do not usually form simultaneously as diagrammed.

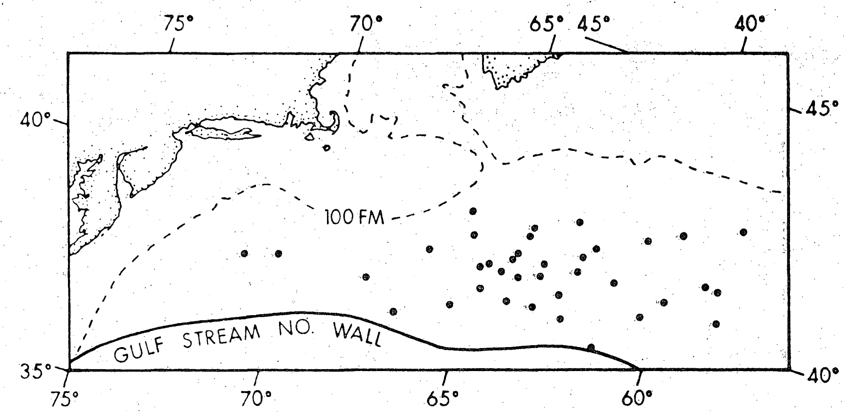

Figure 9. Estimated center positions of Gulf Stream warm core rings when newly formed during the years 1974-78.

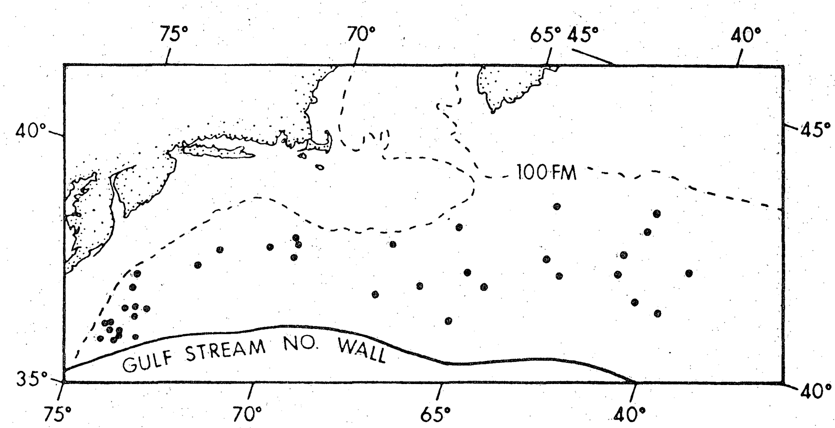

Figure 10. Estimated center positions of Gulf Stream warm core rings immediately prior to their destruction during the years 1974-78.

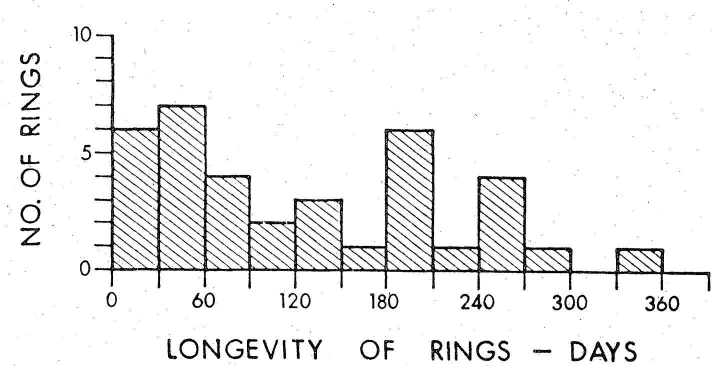

Figure 11. Longevity of Gulf Stream warm core rings during the years 1974-78.

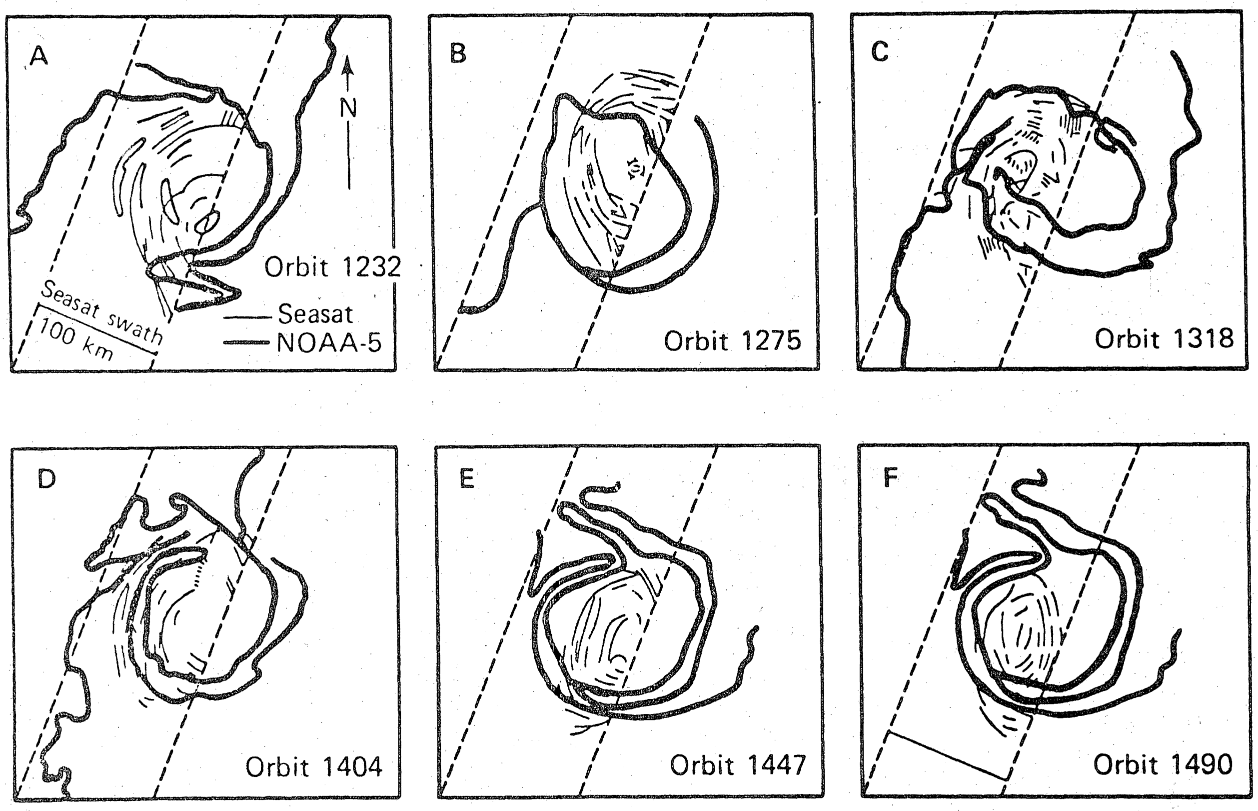

Figure 12. Correlations between NOAA-5 imagery and SAR imagery for six orbits of Seasat SAR over a Gulf Stream warm core ring during September-October, 1978. The differences in times of images in hours are: A,-4; B,+10; C,+22; D,-4; E,-39; F,-50 (+ = SAR earlier) (After Lichy, 1981).