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

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Abstract

Scanning radiometers operating in thermal infrared wavelengths have provided the only regular, operationally available satellite remote-sensing data on the changing patterns of ocean circulation, water mass distributions and water mass interactions. Continuing analyses of infrared data for the waters of the Northwest Atlantic are described for the period since 1973 when very high resolution radiometers (VHRR) were deployed in NOAA polar-orbiting satellites. The significance of these analyses are considered in the context of a brief summary of principal surface circulation characteristics of this ocean region: shelf-slope water frontal movements, meandering of the Gulf Stream, generation and movement of Gulf Stream warm-core rings, and interactions of these features. The varying effectiveness of satellite infrared data for study of different components of the surface circulation regime are discussed. Possible improvements in application of satellite remote sensing for these studies are considered in relation to: more effective use of data from infrared sensors and operational use of data from sensors for the visible and microwave bands of the electromagnetic spectrum.

Introduction

This paper 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 by the National Oceanic and Atmospheric Administration (NOAA) aboard polar-orbiting environmental satellites. Infrared sensing has continued to provide the only operationally available data from satellites which can be used to analyze ocean circulation and water mass distributions. Fortunately, the Northwest Atlantic is one of the most favorable areas of the world's oceans 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" is used here to signify that the analyses have not been based on numerical temperature data but rather on (a) charts of the surface positions of thermal fronts prepared by the NOAA National Earth Satellite Service and the U. S. Naval Oceanographic Office (e.g., Fig. 1 and 4), and (b) thermal infrared imagery from NOAA polar-orbiting and geostationary satellites. In the charts, the positions of permanent fronts and prominent transient fronts are composited to Mecator projection from the clear-sky portions of thermal infrared imagery over periods of a few days to a week. The imagery, processed in shades of gray, reveals only the relative strength of thermal gradients with no correction for variation in atmospheric interference. However, image-processing 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 facts should be considered, one of which is oceanographic and the other technological. The first is that the continental shelf and slope, 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 is that, prior to orbiting of second generation environmental satellites in 1973, the influence of oceanic conditions on the fishing grounds was essentially unknown. In earlier years, no geographically comprehensive data were routinely available on the variable patterns of circulation in the oceanic regime, even though the large magnitude of that variability had long been recognized, largely from shipboard investigations. In contrast, routine data on the astronomical influence of tide and on such meteorological influences 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 fishing grounds of the continental shelf and slope.

Although the satellite radiometers only measure infrared radiation from the surface film of the ocean, the resulting data provide a new level of understanding of circulation in the Northwest Atlantic, not only at the surface but also to hundreds of meters beneath the surface. 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 their subsurface configurations 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 outweighted by much larger horizontal movement of the fronts in their entirety throughout the water column.

It should be recognized that the satellite infrared data also provide an integrated picture of how permanent fronts move relative to one another and how water masses interact through the major cross-frontal exchange process of Gulf Stream ring (eddy) production and through the effects of these rings on the waters around them. In this context, it has become clear that warm-core Gulf Stream rings warrant particular attention by fishery oceanographers, because their oceanic 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 fishery resources are principally concentrated.

This paper provides information on how satellite infrared data have been used in oceanographic research on frontal movements and water-mass interactions off the northeast coast of the United States, outlines the applicability and limitations of such data, and considers possibilities for improvement in the use of remote-sensing techniques.

Use of Satellite Infrared Data in Oceanographic Research

Two types of analysis have been carried out annually since 1974 by the Atlantic Environmental Group of the U. S. National Marine Fisheries Service, principally with satellite infrared data. These relate to (a) variation in the position of the shelf-slope water front from Georges Bank to Cape Romain, South Carolina, and (b) anticyclonic warm-core Gulf Stream rings off northeastern United States and eastern Canada.

Analyses of variation in position of the shelf-slope water front were based on Satellite-derived Gulf Stream Analysis charts issued weekly by the NOAA National Environmental Satellite Service until May 1980 and subsequently on Oceanographic Analysis charts (Fig. 1) issued three times a week by the NOAA National Weather Service and National Earth Satellite Service. Surface positions of the front were recorded from the charts by measuring its distance offshore or onshore of the 200-m isobath along several standard bearing lines (Fig. 2 and 3). The influence of Gulf Stream warm-core rings on the position of the front has also been evaluated from these charts. The most recently published of these analyses (for 1979) was by Hillard (1981).

Analyses of anticyclonic warm-core Gulf Stream rings were based on Experimental Ocean Frontal Analysis charts issued weekly by the U. S.Naval Oceanographic Office (Fig. 4) from January 1974 to May 1978, on Satellite-derived Frontal Analysis charts issued weekly by the NOAA Environmental Satellite Service from June 1978 to May 1980, and on Oceanographic Analysis charts issued three times a week by the NOAA National Weather Service and National Earth Satellite Service since May 1980 (Fig. 1). Infrared imagery from NOAA geostationary satellites since 1976 and from NOAA polar-orbiting satellites since 1978 has been used to reevaluate, modify, and add to warm-core ring positions on the charts. The movement of each ring which occurred west of 60° W has been tracked (Fig. 5 and 6), and its origin, periodic interactions with shelf and Gulf Stream water, and ultimate destruction have been briefly described from the charts, infrared imagery, and other available data. The most recently published of these analyses was by Fitzgerald and Chamberlin (1981).

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) was by Crist and Chamberlin (1981).

Satellite infrared data have been extensively used to investigate the effect of oceanographic conditions on waste disposal in the 106 Mile Dumpsite located southeast of Hudson Canyon. The data have been used in conjunction with shipboard observations to estimate

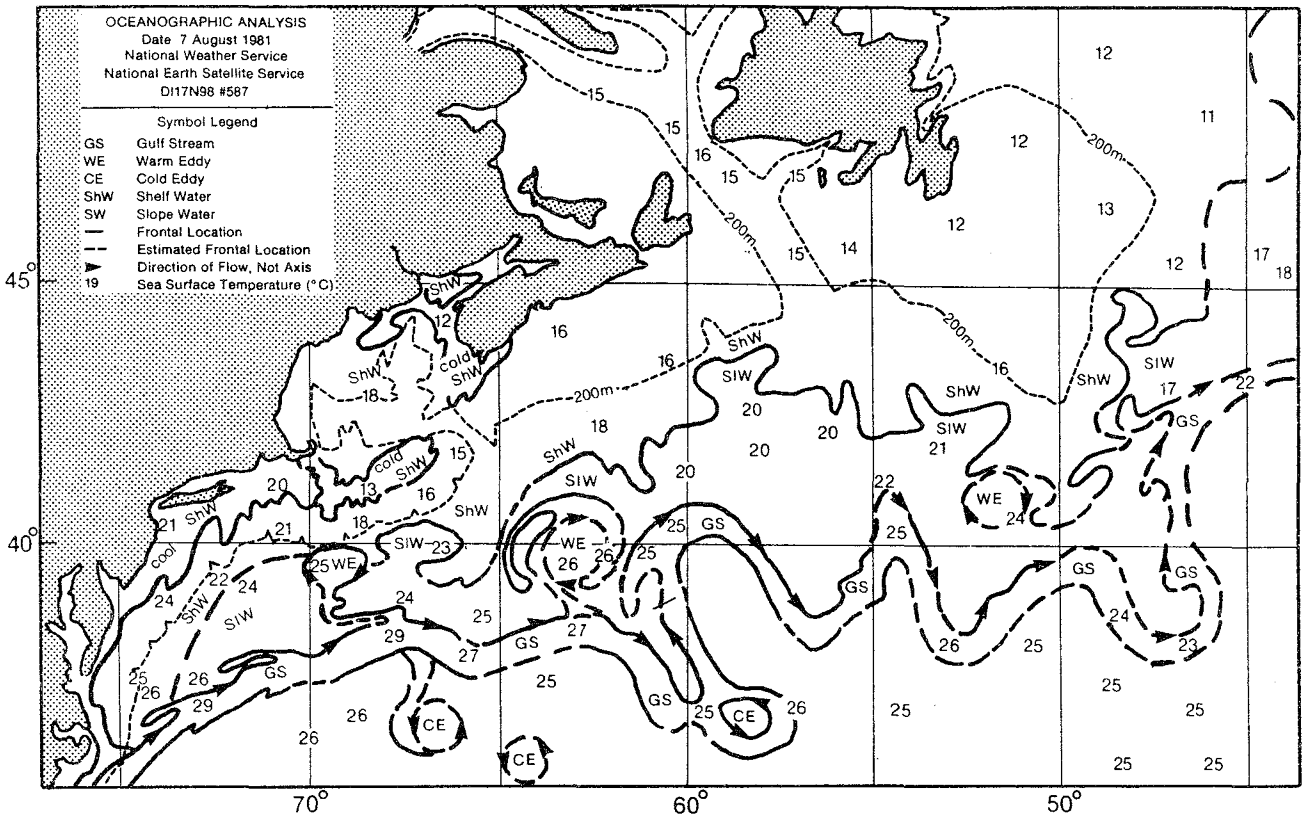

Fig. 1. NOAA National Weather Service and National Earth Satellite Service, Oceanographer Analysis map for 7 August 1981.

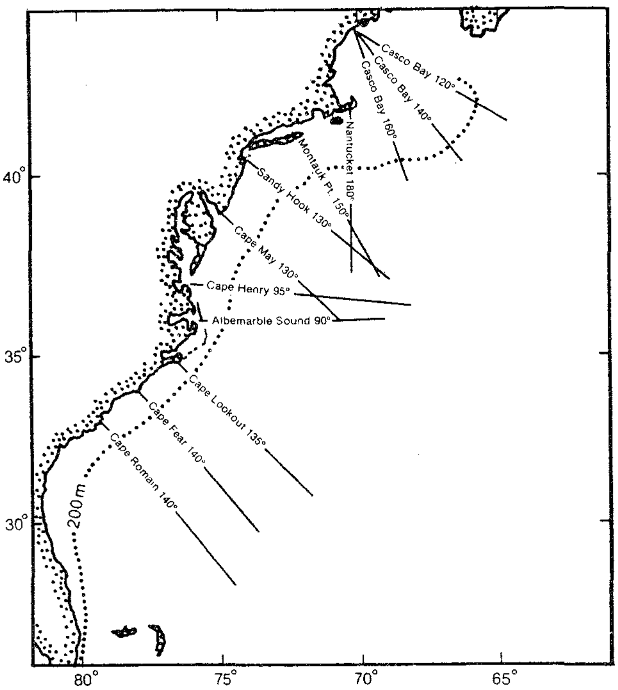

Fig. 2. Reference points and bearing lines used to portray the variation of the position of the shelf-slope water front off eastern United States relative to the 200-m isobath (after Hilland, 1981).

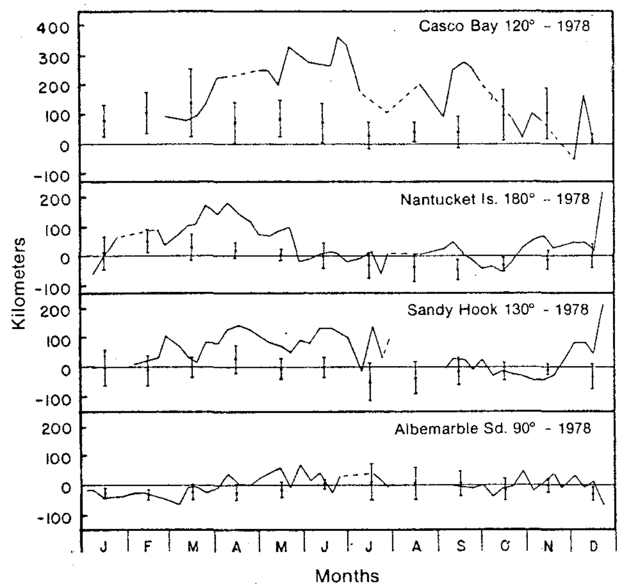

Fig. 3. Shelf water frontal positions in 1978 relative to the 200-m isobath (positive is seaward) on selected bearing lines from Fig. 2 (after Hilland and Armstrong, 1980). (Dotted lines indicate gaps in the data of 2-4 weeks; breaks in lines indicate gaps greater than a month; mean monthly positions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

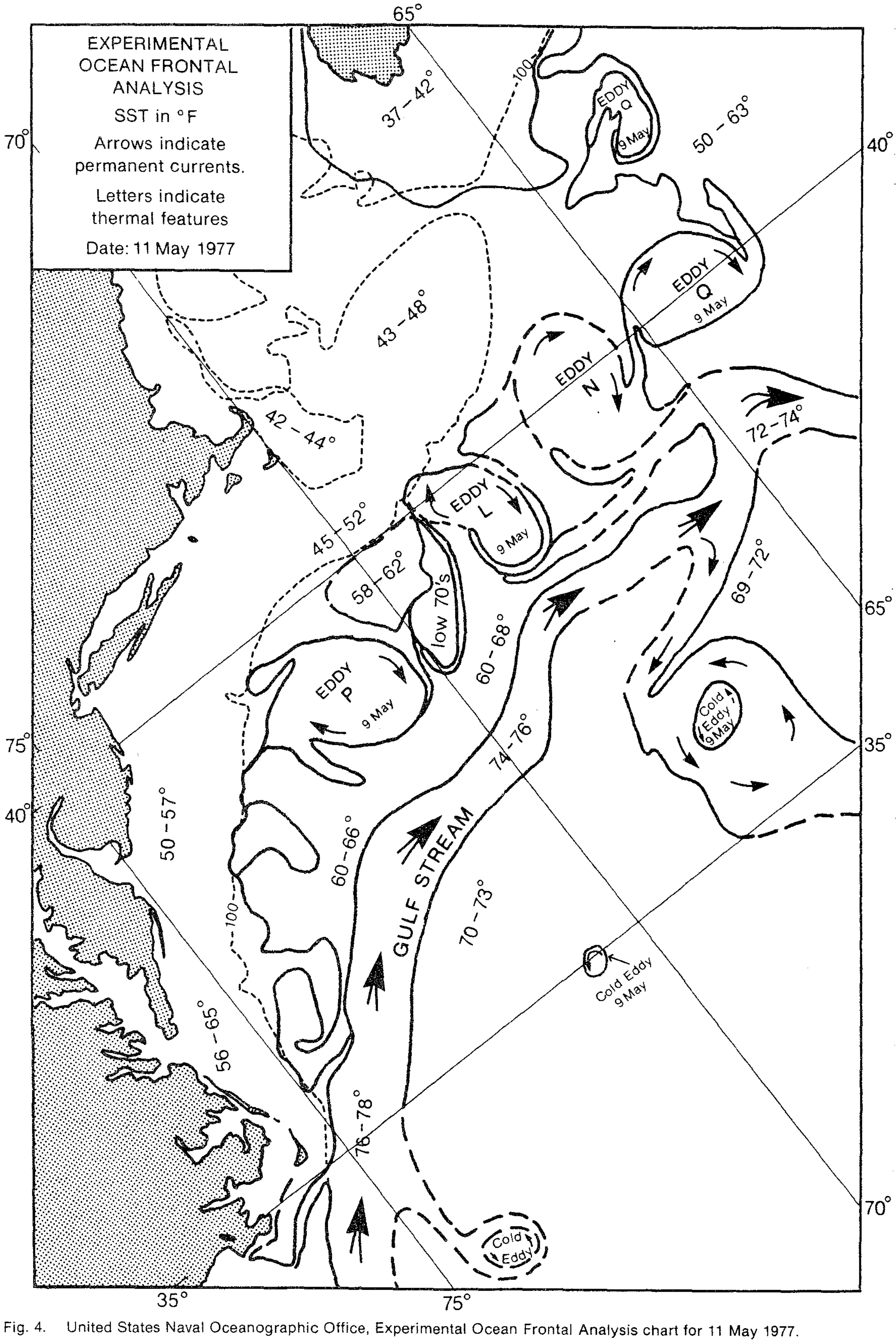

Fig. 4. United States Naval Oceanographic Office, Experimental Ocean Frontal Analysis chart for 11 May 1977.

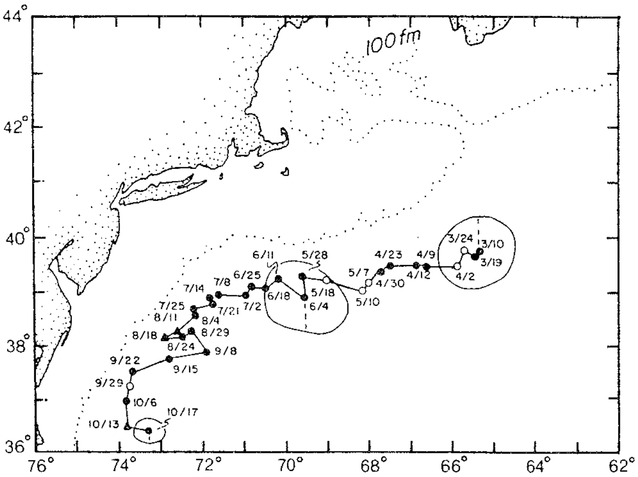

Fig. 5. Track-line for Gulf Stream warm-core ring 80-A during 1980 (after Fitzgerald and Chamberlin, 1982). (Dots are estimated center positions on the indicated dates; ring boundaries interpreted from oceanographic analysis charts and satellite infrared imagery are included for selected dates.)

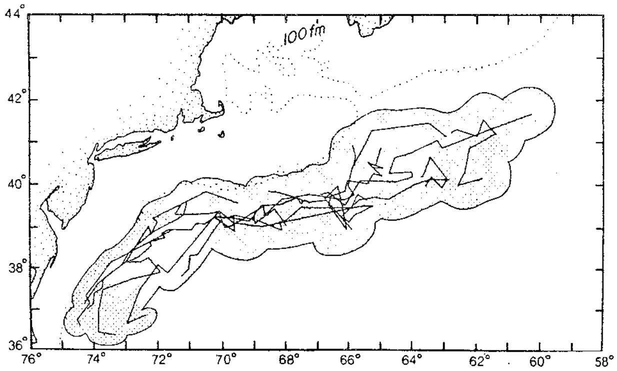

Fig. 6. Composite track-lines of Gulf Stream warm-core rings and envelope of composited ring surface boundaries during 1980 (after Fitzgerland and Chamberlin, 1982).

variability in the relative volume of shelf, slope and warm-core ring water within the dumpsite, 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 by satellites and shore-based radio-direction instruments. A recent report was by Bisagni (1981).

Multiple-year "climatological" research is now in progress, based on data derived from satellite imagery 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. Another project involves time-dependent correlations of the surface areas of shelf water, slope water and warm-core rings off the northeastern United States.

Water Masses, Gulf Stream Meanders and Rings

North of Cape Hatteras, the Gulf Stream turns northeastward over deep water and tends to meander with increasing amplitude downstream. The deep area between the Gulf Stream and the continental slope is occupeid by slope water which is intermediate in properties between the colder, less saline shelf water and the warmer, more saline Gulf Stream water (Fig. 7). The permanent steep temperature and salinity gradient (front), which separates shelf and slope water, makes contact with the bottom on the outer continental shelf and usually appears at the surface some distance farther offshore. During the summer, temperature contrast across the front may disappear at the surface. Flagg and Beardsley (1978) reported on the stability of the shelf-slope water front south of New England, but, during the spring and summer of 1978, the front was far offshore from its normal position at the surface off Georges Bank and the Middle Atlantic coast (Fig. 3; Chamberlin, 1978; Hilland and Armstrong, 1980).

Meanders reaching amplitudes of 150 km and greater often detach from the Gulf Stream and form into rotating masses of water called Gulf Stream rings or eddies (Fig. 8). Warm-core rings form in the slope water by detachment of meanders on the shoreward side of the Gulf Stream. 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 high as 140 cm/sec (Cheney, 1978). The rings have a warm core because they enclose Sargasso Sea water that has crossed the Gulf Stream within the originating meander (Fig. 8). Greatest in area near the surface (Fig. 7A), newly-formed rings have ranged in diameter from about 150 to 230 km and reached a depth of over 2,000 m. Unlike Gulf Stream meanders, which move in the direction of the Stream, warm-core rings have typically moved in the opposite direction at average speeds up to 15 cm/sec over periods of several days. However, they have usually moved at less than half this speed and often stopped and moved in irregular directions for days or even weeks (Fig. 5). Because most of the warm-core rings seen off New England and the Middle Atlantic coast have formed southeast of Georges Bank (Fig. 9A), where Gulf Stream meanders often reach high amplitude, many have been destroyed near their place of origin (Fig. 9B) within a few weeks or months after formation by encountering a meander. Those which escape destruction and reach the longitude of Cape Cod have usually persisted for a few to several more months until they eventually are resorbed by the Gulf Stream in the vicinity of 36° N 74° W, where the Stream runs close to the continental slope (Fig. 9B). The frequency distribution of ring longevity (Fig. 10) provides direct evidence that warm-core rings have tended to be either short- or long-lived. The production of rings, observed in the slope water west of 60°W during 1974–80, varied from six in 1974 to 11 in 1979 (Fitzgerald and Chamberlin, 1981). Variation in the number of rings, simultaneously present, ranged from

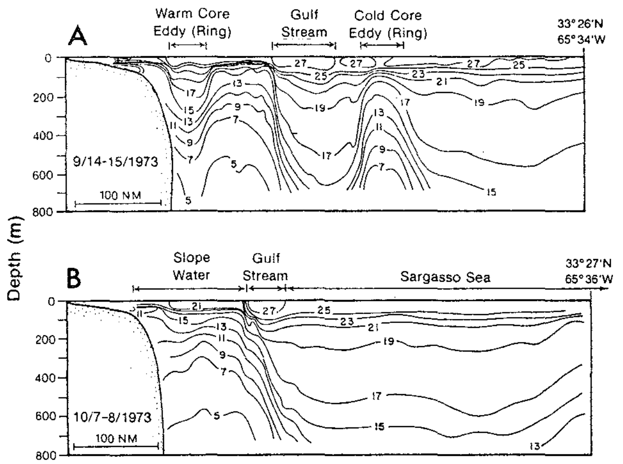

Fig. 7. Vertical temperature profiles on a section from New York toward Bermuda in 1973. **A**, Illustration of a warm-core ring in slope water and a cold-core ring in the Sargasso Sea. **B**, Illustration of temperature structure when no rings were present. (From Gulf Stream Monthly Summary, 9(7), July 1974, U. S. Naval Oceanographic Office).

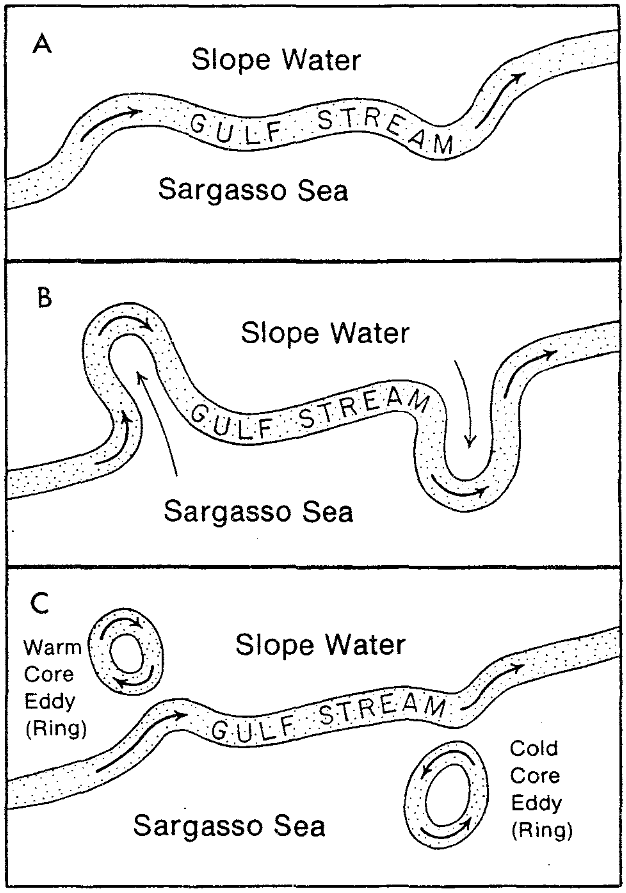

Fig. 8. Diagrams of Gulf Stream ring formation. (Warm and cold core rings do not usually form simultaneously as shown.)

eight during a period of a week or two in early May 1977 (Mizenko and Chamberlin, 1979) to none during a 6-week period from March to mid-April 1978 (Celone and Chamberlin, 1980).

Cold-core rings form in the Sargasso Sea by detachment of meanders on the seaward side of the Gulf Stream (Fig. 8). Opposite in structure to warm-core rings, they rotate counter-clockwise and contain a core of colder slope water (Fig. 7A). Although cold-core rings have been studied more than warm-core rings by oceanographers, they are not at present of direct importance in fishery research, because the oceanic region where they occur has not been found to be biologically productive.

The influence of Gulf Stream warm-core rings and meanders on the continental shelf regime remains poorly understood and is seldom directly evident in satellite infrared imagery, except in the case of offshore "entrainment" of surface shelf water by these features. Nevertheless, it is apparent that the degree of influence must be a function of several characteristics of the rings and meanders: size, number, longevity, location, proximity to the continental slope, velocity of horizontal translation, and rotational speed. The influence is also a function of interactions between the rings and meanders, which often augment the shoreward transfer of Gulf Stream water and energy, particularly when a meander increases in size as the result of merging with a ring. Fortunately, satellite infrared imagery provides direct quantitative data, not only on all the above characteristics of the rings and meanders, with the exception of rotational speed, but also similar information on the interactions of these features.

Three kinds of influence of rings and Gulf Stream meanders on the continental shelf water have been observed: (a) removal of shelf water by "entrainment", (b) injection of slope water and modified Gulf Stream water onto the shelf, and (c) modification of circulation on the shelf. Satellite infrared data, as mentioned above, provide direct information only on the first of these influences (entrainment) because of its visibility at the sea surface.

Injections of slope water and modified Gulf Stream water onto the shelf by warm-core rings have been frequently observed in vertical temperature sections from shipboard data. Pronounced examples have been reported for southwestern Georges Bank (Anon., 1978) and southern New England (Crist and Chamberlin, 1979). Because injection onto the shelf is predominantly subsurface, satellite data provide only circumstantial evidence by showing where this process may be taking place.

Information is scarce on the influence of warm-core rings on shelf circulation outside of entrainment

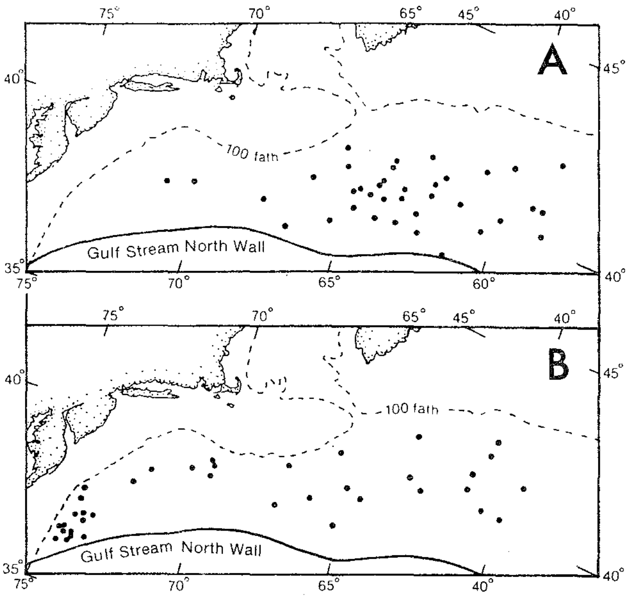

Fig. 9. Estimated center positions of Gulf Stream warm-core rings during the 1974–78 period: (**A**) when newly formed, and (**B**) immediately prior to their destruction.

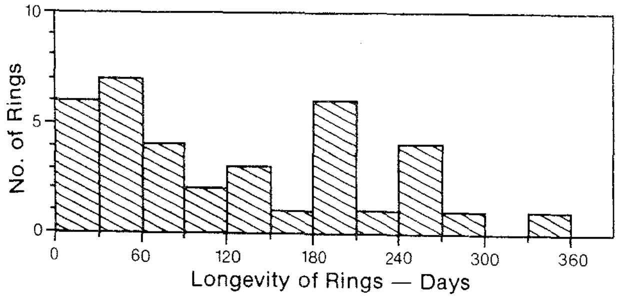

Fig. 10. Logevity of Gulf Stream warm-core rings during the 1974–78 period.

at the surface. However, drogued buoys on southwestern Georges Bank in November 1977 showed reversal of "the expected downcoast (southwestward) mean flow" associated with a warm-core ring (Anon., 1978). Again, as in the case of injections, the satellite data only indicate where such a circulation influence may be taking place.

Applicability of Satellite Infrared Data to Oceanographic Investigations

Permanent fronts and warm-core rings

At the present level of technical development, the most informative application of satellite infrared data to oceanographic investigations in the Northwest Atlantic is in analyses of 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 sub-surface structure of these fronts are fairly well understood, their surface positions are useful indices of their locations in the water column. Furthermore, the positions of these fronts at the surface can be measured and charted more frequently and in more detail from satellite infrared data than is possible from 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 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 whenever their surface thermal patterns become 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 which chill the surface water. 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 the rings can often be estimated from encircling bands of entrained shelf or Gulf Stream water. Off the Middle Atlantic coast during the summer, rings may be invisible in infrared imagery, because surface thermal contrasts may disappear between rings, slope water and shelf water. In such cases, rings can only be located when they are entraining Gulf Stream water. Such entrainment, however, is not usual, because most of the rings in the region, being old, are reduced in size, and remain close to the continental slope away from the Gulf Stream.

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

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 long-period fronts. This contrast may be illustrated by comparing analysis of shelf water (or Gulf Stream water) entrainment by a warm-core ring with analysis of the movements of the ring itself. The positions and surface areas of rings that continue to exist during periods of several days to a few weeks when they are "hidden" from the satellite radiometer by clouds can usually be interpolated with near certainty, particularly if frontal patterns in the vicinity of the rings are visible during part of the period. In contrast, neither the continuity nor the duration of surface entrainment features can be estimated during such periods, because the entrainment process may only last for a few days.

Satellite infrared data are also less informative about transient fronts than permanent fronts, because the process associated with the former are less well understood than those with the latter. For example, the primary information sought by oceanographers is an estimate of volume transport, but 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 cross-sectional area 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. In analysis of water entrainment by rings, the infrared data may be invaluable not only for guiding shipboard observations but also for interpolations during subsequent analysis of the data.

Intermittency has been a normal characteristic of surface entrainment of shelf water (and also Gulf Stream water) by warm-core rings, as evidenced from infrared data, but one that has apparently not been investigated. Although this entrainment must depend on a ring being within some minimum distance from the shelf water source, proximity of ring to shelf water is not a sufficient condition for entrainment. Several years of weekly frontal analysis charts have shown that shelf water entrainment is intermittent even by rings that remain close to the shelf-slope water front.

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 may provide only indirect information, because injections, as seen in vertical temperature sections (e.g. see Crist and Chamberlin, 1979), are most pronounced below the surface and predominantly near the bottom. Nevertheless, the 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 (e.g. correlation of rates and magnitudes of movements of fronts and rings with one another.) In view of the continuity of water masses and the tendency of warm-core rings to move throughout the extent of the slope-water area, the analyses should encompass the entire region from the continental shelf to beyond the Gulf Stream. However, the inclusion of waters eastward of the Scotian Shelf may not be practical because of the greater frequency of cloud cover.

Possible Improvements in Satellite Remote Sensing for Research on Ocean Fronts

Improvements can be made in the use of satellite remote sensing for ocean frontal analyses through more efficient use of the infrared data available from NOAA operational environmental satellites and the 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 affiliated with a regional organization, the Northeast Area Remote Sensing System.

Improvements in use of infrared data

One improvement involves 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.

Another improvement involves the correction of infrared data to sea-surface temperature values. 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 from polar-orbiting satellites (TIROS-N series). This is done through comparison of readings at wavelengths of 3.7, 10.9 and 12 micrometers in the thermal infrared band, to correct for atmospheric interference (Deschamps and Phulpin, 1980; Kidwell, 1981).

Time-compositing of infrared data from geostationary satellites (GOES) can be used to chart sea-surface temperature with more 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 data collection by the geostationary satellites (every 30 min, compared to every 12 hr by 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 printout or as imagery in gray tones. The compositing routine has been under development at the NOAA National Environmental Satellite Service since 1977, with the objective of establishing an operational sea-surface temperature mapping service for the waters off both coasts of the United States. A fixed selection of data from a 6-hr 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-hr period.

A fourth improvement involves the detail and geographical accuracy of the frontal analysis charts. The efforts of the analysts could be made more efficient by providing for the above-mentioned improvements and, in addition, the facilities for automated reformatting of the frontal positions from imagery to a standard map projection.

Use of new satellite remote-sensing technology

Consideration here is restricted to two kinds of remote-sensing technology: Synthetic Aperture Radar (SAR) and 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.

The SAR was successfully deployed 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, (Behie and Cornillon, 1981). They indicate that SAR could be a powerful instrument for detecting ocean fronts. Lichy *et al.* (1981), through comparison with AVHRR thermal infrared red imagery of a Gulf Steam warm-core ring, found that more or less simultaneous SAR images also detected the ring during all six passes over it by SEASAT-1 in September-October 1978. "Characterized by concentric curvilinear or arcuate bands", the ring configurations in SAR imagery were smaller than in AVHRR, but the ring positions were in close agreement (Fig. 11). Entrained shelf water encircling the ring does not seem detectable in this SAR imagery although prominent in the infrared. However, the nearly all-weather capability of SAR would give it some distinct advantages over AVHRR in providing data for analysis of ocean frontal movements, if this sensor is again deployed in satellites.

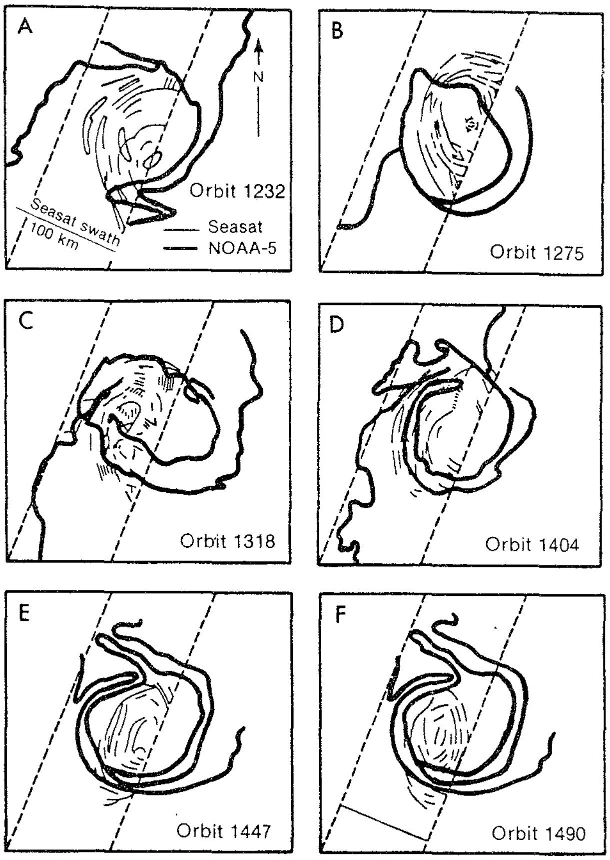

Fig. 11. Correlations between NOAA-5 imagery and SAR imagery for six orbits of SEASAT SAR over a Gulf Stream warm-core ring during September-October 1978 (after Lichy *et al.*, 1981). (The differences in times of SAR images relative to NOAA-5 were: **A** (-4 hr), **B** (+10 hr), **C**(+22 hr), **D** (-4 hr), **E** (-39 hr), **F** (-50 hr).

The CZCS, successfully operated since 1978 in NIMBUS-7, a NASA research satellite, was designed primarily to measure ocean color variations in four spectral bands. In offshore waters, the principal color variations detectable by CZCS data apparently relate to concentrations of chlorophyll *a* in phytoplankton. Therefore, detection of ocean fronts and circulation patterns with CZCS or other multi-spectral ocean color scanners will largely depend on differences in chlorophyll concentration between water masses. Peter Cornillon (Univ. of Rhode Island, pers. comm.) has processed a limited quantity of CZCS images of Northwest Atlantic areas and was able to locate a warm-core Gulf Stream ring in imagery of both visible and thermal infrared wavelengths. Investigation is needed on the possibility of using CZCS to locate ocean fronts and warm-core rings when sea-surface thermal contrasts are negligible.

Summary

1. Measurements of thermal 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 environmental satellites were placed in orbit. The unique capability of these satellites to provide frequent, detailed data on these movements and interactions 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 northeastern United States and Nova Scotia have shown some of the potential of satellite infrared data, but a broader range of analyses are needed to fully realize this 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-term fronts than for analyses of transients fronts, such as those associated with the entrainment of shelf water or Gulf Stream water by warm-core eddies. The infrared data are invaluable, however, as a guide to sea-going investigations of processes with which both types of fronts are associated.

4. Improvements can be made in the use of satellite remote-sensing data for analyses of ocean frontal movements and water-mass interactions through more efficient use of the satellite infrared data presently available and through the use of new satellite environmental sensors to overcome inherent limitiations of infrared sensors.

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