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Progress on the Gulf Stream

by P. L. Richardson

The Gulf Stream, a large and complex Atlantic Ocean current, has intrigued navigators and explorers since it was first identified by Juan Ponce de Leon, Spanish discoverer of Florida, in 1513. In a previous article Louis De Vorsey described the first attempts to map the current's path in the 18th century. Here, P. L. Richardson explains how the methods of the modern science of oceanography have provided a better understanding of the Gulf Stream

THE GULF STREAM system is known to transport heat in the ocean and to affect weather and climate. It is a large complex current system which varies rapidly, and these variations make measuring the Gulf Stream and learning about its dynamics difficult.

The dominant variations of the Gulf Stream are in the form of meanders and eddies. As the Gulf Stream shoots eastward from North Carolina, it remains quite narrow, 100 kilometres in width, and meanders from side to side much like a river on a nearly level flood plane. The Stream's meanders shift position rapidly within periods of several days. Frequently, Gulf Stream meanders increase in amplitude and form closed loops which separate from the main current. These large eddies, often 300 kilometres in diameter are called Gulf Stream rings because they consist of a ring of Gulf Stream water. A ring formed south of the Stream has a counterclockwise rotation and a cold core consisting of water originally located in the Slope Water region north of the Stream. As such a ring breaks off from the Stream, the Slope Water is trapped in its centre and is transported across the Stream. Once separate from the Stream, a ring drifts around the ocean, generally westward, and occasionally interacts with the Gulf Stream and other rings.

All attempts to chart the Gulf Stream have been confronted by its variability, its meanders and rings. One problem is that of trying to measure a current system several kilometres deep, hundreds of kilometres wide and thousands of kilometres long that is changing shape and position rapidly. A single ship, because of its speed, can only measure a small portion of the current before its structure has changed. In comparison to charting ocean currents, charting the sea floor is rather easy because the bottom topography stays still. Of course, there are long term changes due to continental drift, erosion, and volcanic eruptions but the variations of the main features of the sea floor relief are small or slow in comparison to the meanders and eddies of the Gulf Stream system. Interpreting the complicated measurements and displaying the results is not easy.

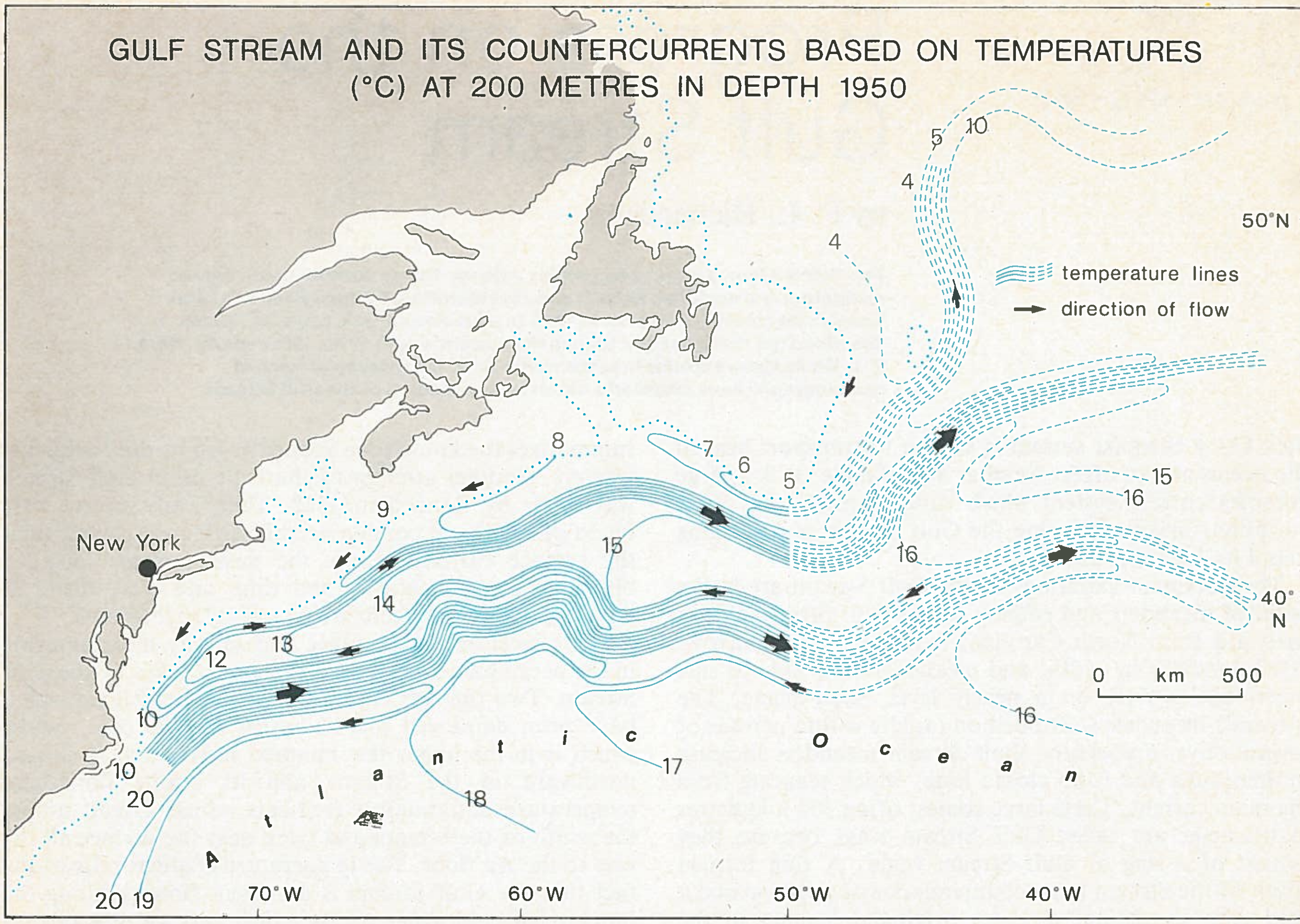
Oceanographers have usually resorted to two methods to plot the Gulf Stream. The first is to combine data taken at different times and to prepare charts of the mean currents. The second is to plot data taken during a relatively short time, freezing the Gulf Stream in the form of a photograph. A mean current chart, and also the first good chart of the Gulf Stream, was made by Benjamin Franklin and Timothy Folger in 1769 (see THE GEOGRAPHICAL MAGAZINE, April 1980). This chart shows the mean limits of the Gulf Stream, the envelope of the meanders, and current vectors characteristic of velocities in the high speed core of the Stream. The chart summarizes the knowledge learned at sea by the Nantucket whalers. Another attempt to chart the mean Gulf Stream was made by Rennell in 1832. These early charts were based primarily on combining ship drift measurements of the surface currents. Since the measurements included observations in meanders and rings and were made at different times, the results were not easy to interpret.

More recently, temperature and salinity measurements in the ocean have been used to construct maps of the Gulf Stream. Two thermal characteristics of the Stream which have been employed are its warm surface core - water which is in the upper few hundred metres and is carried northward in the Stream - and its strong horizontal temperature and salinity gradients which extend across the width of the Stream and from near the surface all the way to the sea floor. The temperature gradient reflects the fact that the Gulf Stream is a current flowing along the juncture of cold water on the north and warm water on the south.

Thus charts of the temperature and salinity field give the location of the Stream, and the velocity field has been calculated from them. Several charts of the mean current have been constructed using temperature, salinity and inferred velocity, and although these charts agree in describing the mean Gulf Stream, they differ in portraying the Gulf Stream extension - the North Atlantic current - and recirculation. Is the Gulf Stream very broad with a significant branch flowing toward northern Europe or is it much smaller and contained entirely west of 40°W? Part of the difficulty in determining the correct path of the Gulf Stream recirculation is that it is dominated by strong eddies and in their presence the mean is difficult to resolve.

Charts of the mean currents are a step forward in our understanding of the Gulf Stream, but they are not very informative about the real Gulf Stream. One could never expect that the instantaneous Gulf Stream flow would ever look like that shown on the mean charts. The act of averaging the data blurs and sometimes totally obscures real features of the Stream. Just like a 'mean human' would be of slight help in understanding the dynamics of society, the mean Gulf Stream is not very helpful in understanding the dynamics of the real Gulf Stream system. In order to understand the ocean we need to know how individual eddies develop, interact with other eddies, and decay. One way to do this is by making a photograph or synoptic picture of the Gulf Stream system and then examining this for important features. By making repeated synoptic charts it is possible to study the time changes and interactions within the system. This is exactly what recent eddy studies are doing.

The first attempted synoptic chart of the Gulf Stream



was drawn in 1772 by William De Brahm (see THE GEOGRAPHICAL MAGAZINE, April 1980) who followed the Gulf Stream by ship over a 1000-kilometre section of its path and plotted the observed Gulf Stream plus an extrapolation of its course to the east. More recent, 20th-century, attempts to show the instantaneous Gulf Stream reveal the true complexity of the Gulf Stream system.

The real Gulf Stream consists of a series of currents and countercurrents and intense rings. One chart emphasizes the separate currents and countercurrents while another emphasizes the eddies. The truth about the system probably lies somewhere between the two charts. A synoptic chart of the Gulf Stream system is similar to an ocean weather map; the Gulf Stream and eddies are analogous to the atmospheric jet stream and its cut-off 'high' and 'low' pressure cells. Gulf Stream rings can be thought of as severe oceanic storms, regions where strong currents and temperature and salinity gradients are found.

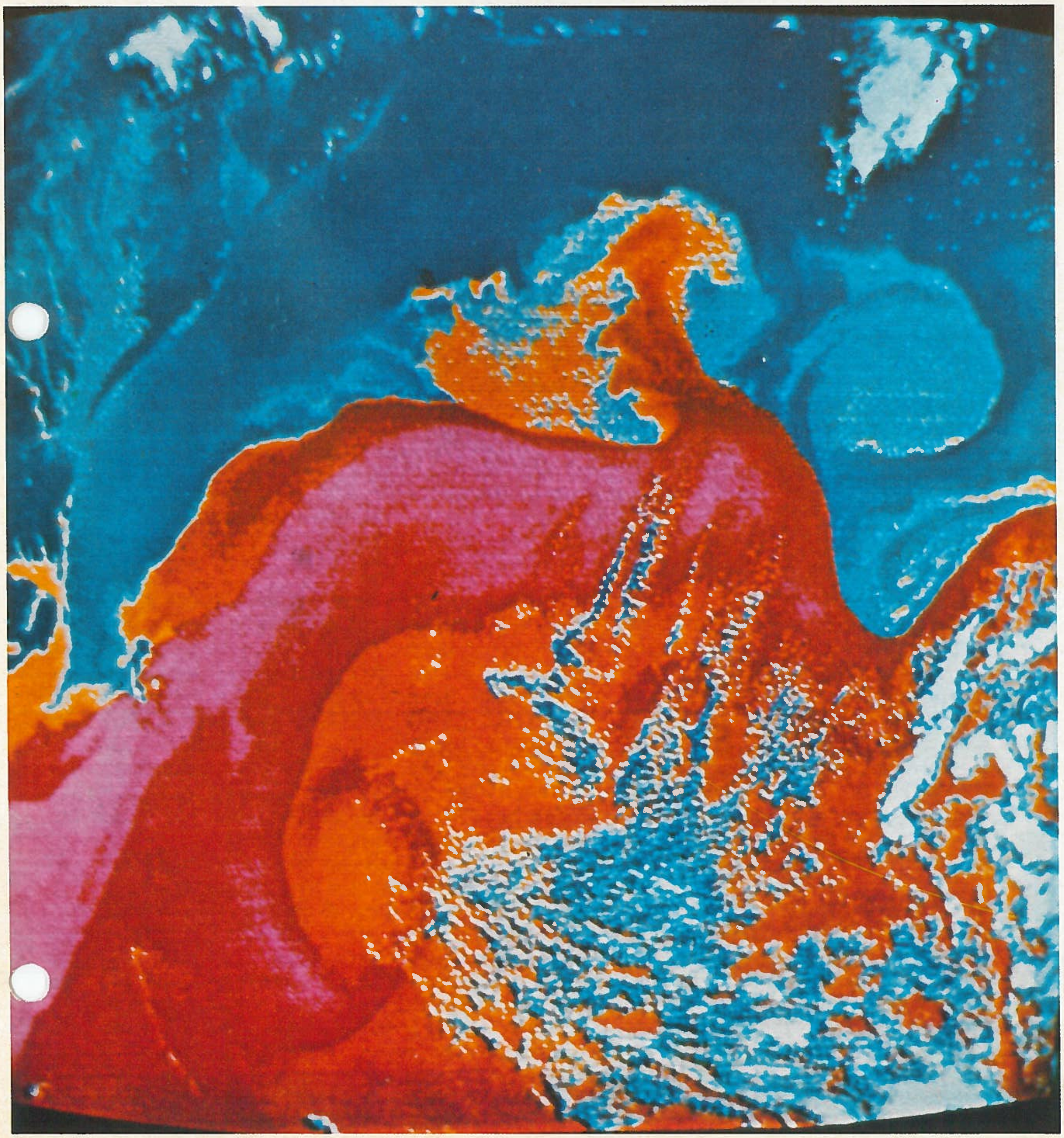
Satellite infrared images have given new information about the distribution of surface temperature of the ocean. Frequently the position of the Gulf Stream is evident from its warm core; eddies and fronts are also often visible, manifested by a particular temperature signal. Although the complex surface temperature field is not easy to interpret without supporting measurements in the water column the images can be used to study the evolution of rings and their interaction with the Gulf Stream. Unfortunately the sky over the Gulf Stream is often cloudy and the temperature gradient at the ocean surface becomes small in summer, limiting the usefulness of the images.

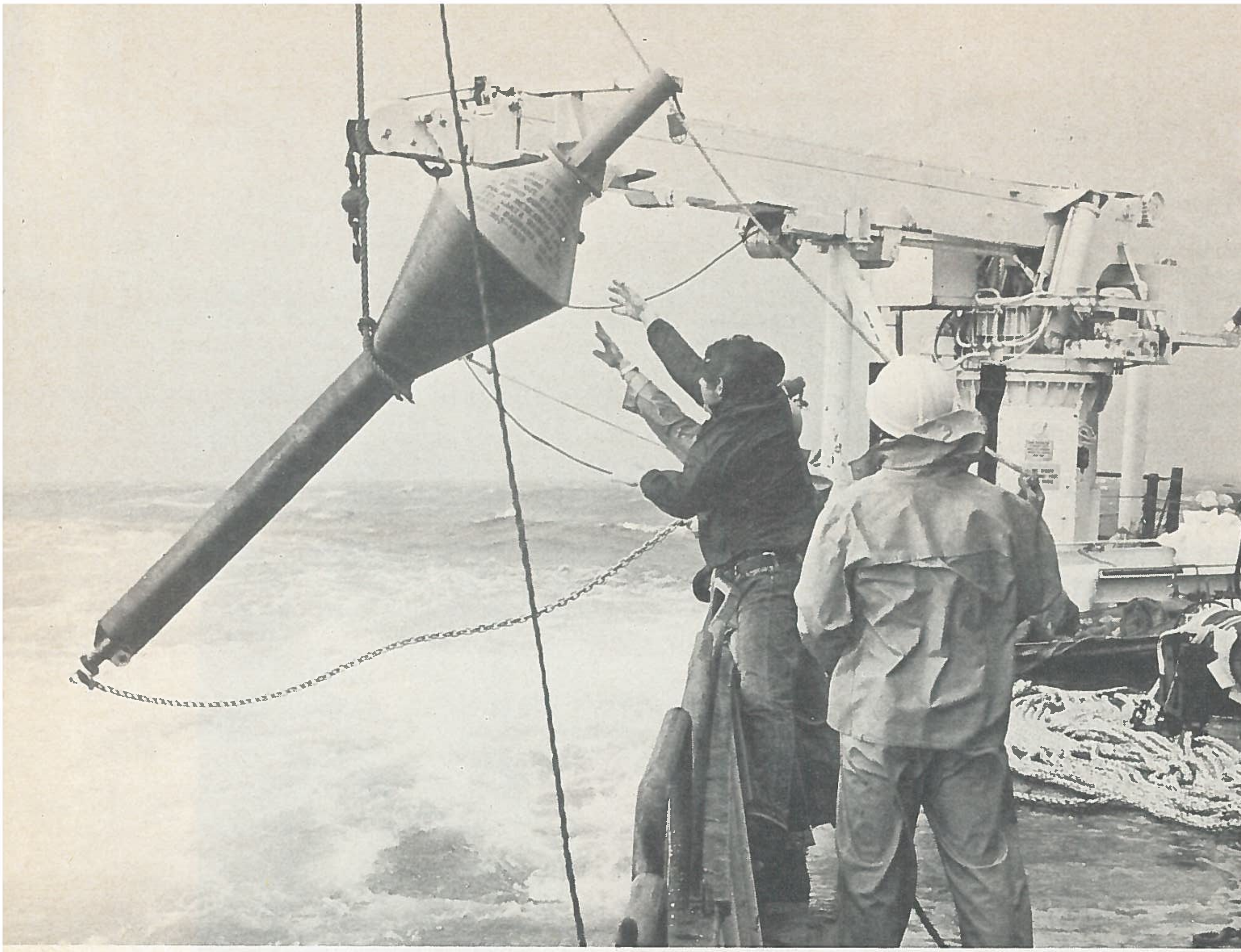
During the last twenty years scientists have realized that most of the ocean's energy is contained in the form of eddies and that the eddies were probably doing the main job of energy transport in the ocean. In order to understand the dynamics of the oceanic circulatory system an understanding of the role of the eddies is necessary. In recent years several large field experiments focused on Gulf Stream rings and their weaker relations, mid-ocean eddies. As these experiments come to fruition, oceanographers are recognizing that many different species of eddies coexist.

Modern eddy research calls for new and sometimes esoteric ways of displaying the results. Some of the more straightforward methods consist of charting the distribution of kinetic and potential energy. In one plot of the Gulf Stream's kinetic energy the contribution of the mean currents and the fluctuations, the eddies, was separated. The eddies were found to be twice as energetic as the mean in the swift mean current region but ten to 100 times as energetic as distance from the main Gulf Stream current increased. Other methods used to visualize the eddies consist of preparing time series of characteristics including velocity or temperature, usually from rather limited regions, and displaying the results on special graphs called phase propagation plots. Often a film of successive patterns is the best way to see the eddy motion.

Gulf Stream rings are the strongest of ocean eddies, and are quite easy to visualize. A study of rings from 1976-1978 measured the life history of two rings. The idea behind the experiment was to find a newly formed ring, to follow it during its life cycle and to make repeated measurements of its physical, chemical, and biological structure and their changes with time. Measurements included satellite images, free-drifting buoy trajectories, vertical profiles of velocity, temperature, salinity, chemical nutrients and biological net tows. Most of these data are still being analyzed by the team of scientists who

The Gulf Stream consists of meandering currents, counter-currents (left) and eddies. It begins off the Straits of Florida and travels north-eastwards before leaving the coast off North Carolina. (Right) southern portion of the Gulf Stream off Miami, Florida. Frequently, meanders in the main current increase in amplitude forming loops which separate as eddies. Two warm eddies and a cold eddy are represented respectively as red-orange and blue circles in a colour-enhanced NOAA-4 satellite infrared image (below) of the Gulf Stream in April 1974





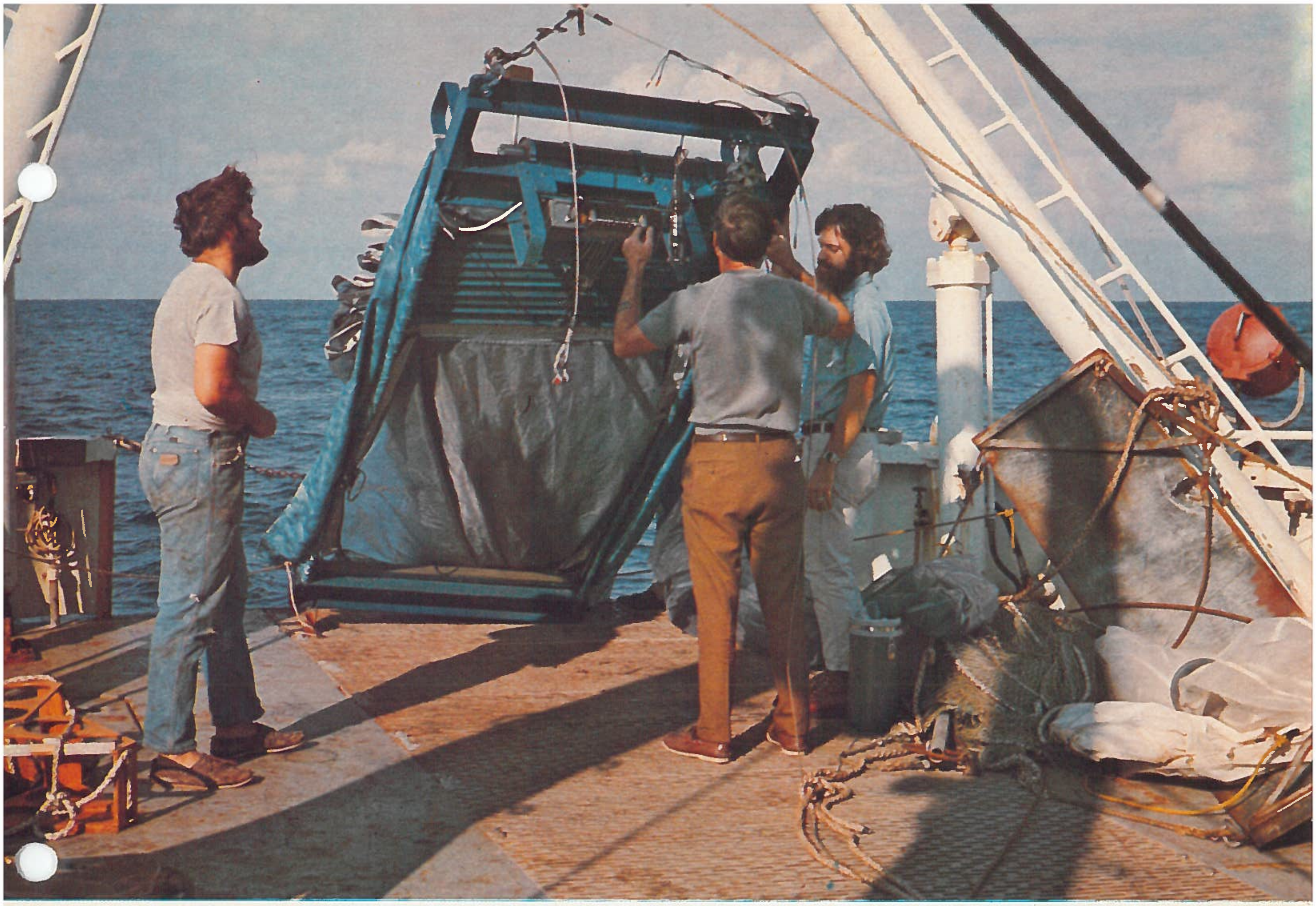
Measurement and charting of the Gulf Stream poses many problems. The system of currents is several kilometres deep, hundreds of kilometres wide, thousands of kilometres long and rapidly alters its shape and position. In addition the presence of many eddies at any specific time, some of which are connected to the Gulf Stream, complicates measurement. To gain a better understanding of the mechanisms of the Gulf Stream scientists are studying variations of the whole system with particular attention to eddies. In 1976-77 two eddies were studied and for the strongest, ring 'Bob', many sets of measurements were taken from the research vessel *Knorr*. Path of free drifting buoy (above) was tracked by satellite. One-square metre of trawl (above right) sampled plankton, salinity, temperature and net speed. Ten-square metre of trawl (below right) sampled biological activity

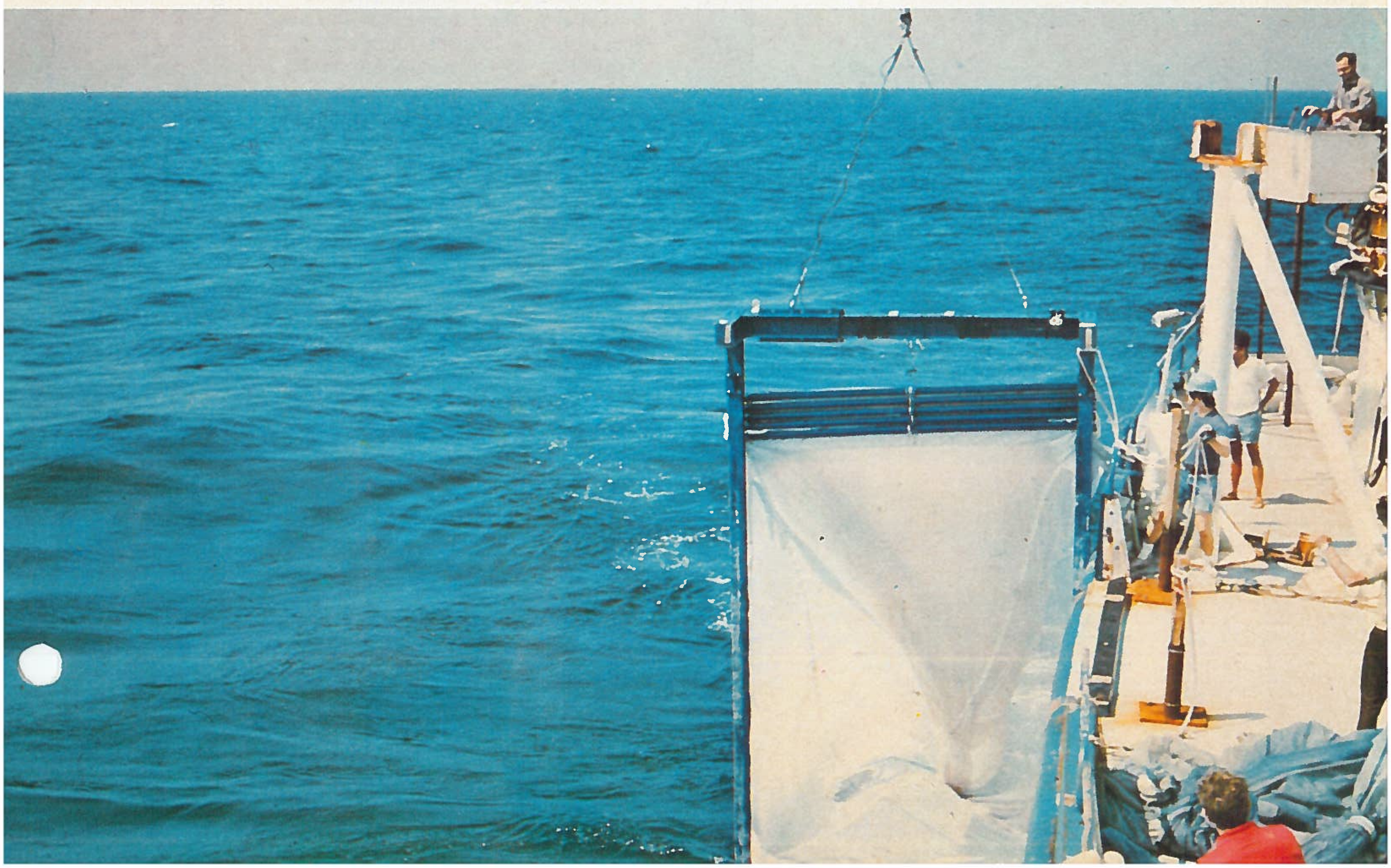
participated in the experiment.

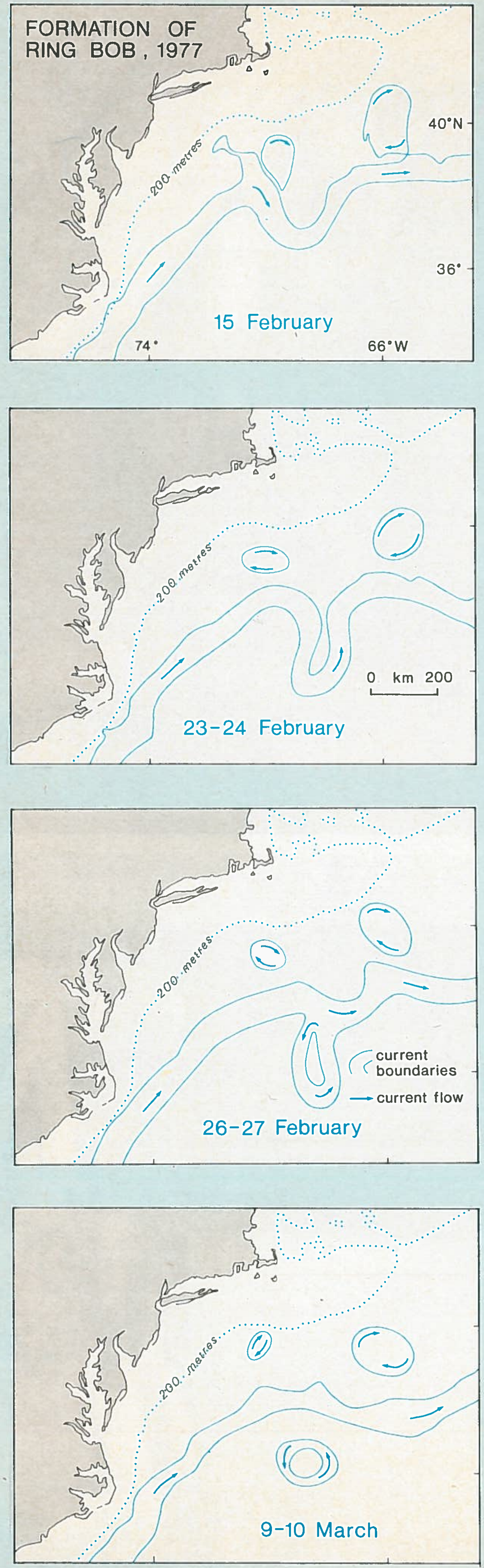
The study concentrated on a ring named 'Bob'. The scientists watched Bob form in February 1977 with the help of an excellent series of infrared images from the NOAA 5 satellite. In April 1977 the research vessel *Knorr* sailed into Bob and those on board found an intense ring whose cold slope water core which they could see, feel and smell from the deck of the ship. Immediately upon entering the central part they noticed a seaweed smell, similar to that of a seashore on a summer day. The water was obviously green and turbid as compared to the clear and deep blue of the nearby Gulf Stream and Sargasso Sea. The temperature of the surface water in the centre was 15°C, nearly 10° colder than the surrounding water; this difference was reflected in the air temperature. A temperature section through Bob provided convincing proof of the strong temperature gradient in the ring. Bob's cold core was observed to extend all the way to the sea floor, 5000 metres deep, although the deep temperature gradient was significantly weaker than that observed at the sea surface.

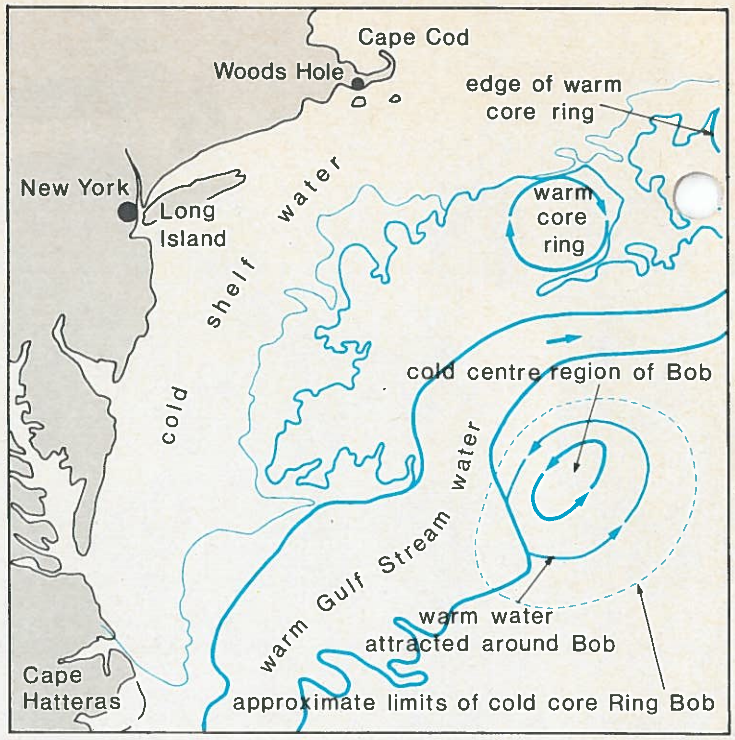
One remarkable aspect of the study was that for the first time an excellent series of data covering a ring's life from birth to death was obtained. Results suggest that Bob's life consisted of four main stages. First, Bob formed in February 1977 and remained nearly stationary for a month. Second, during April Bob became attached to the Gulf Stream, exchanged water and energy, went downstream and reformed as a separate ring in May. Third, during June, July and August Bob drifted slowly south-westward through the Sargasso Sea. Fourth, in September 1977 Bob coalesced with the Gulf Stream and was lost after a lifetime of seven months.

From April to September the movement of Bob was continuously measured by a free-drifting buoy tracked by NASA with the Nimbus F satellite. The buoy looped around Bob's centre with a characteristic period which ranged from two to three days, a diameter of eighty kilometres and a speed of 125 centimetres per second. The trajectory shows the rapid, twenty centimetres per second, eastward velocity where Bob was attached to the Gulf Stream and the slower, five centimetres per second, velocity south-westward through the Sargasso Sea. As Bob coalesced with the Gulf Stream, the buoy was

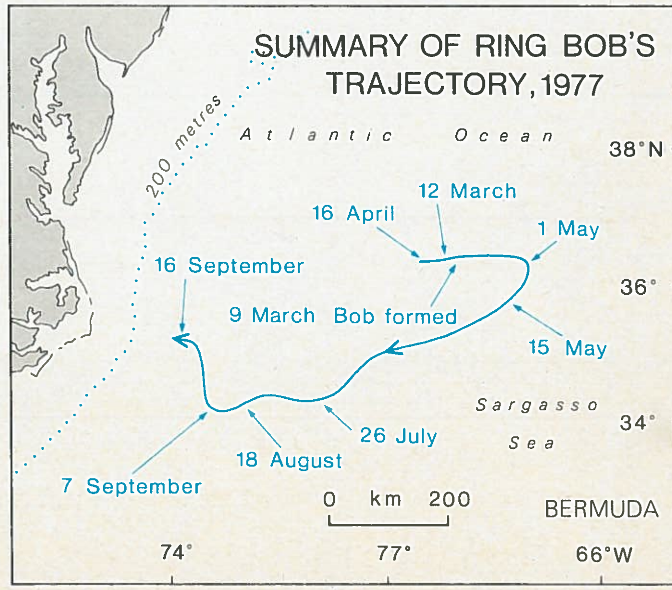


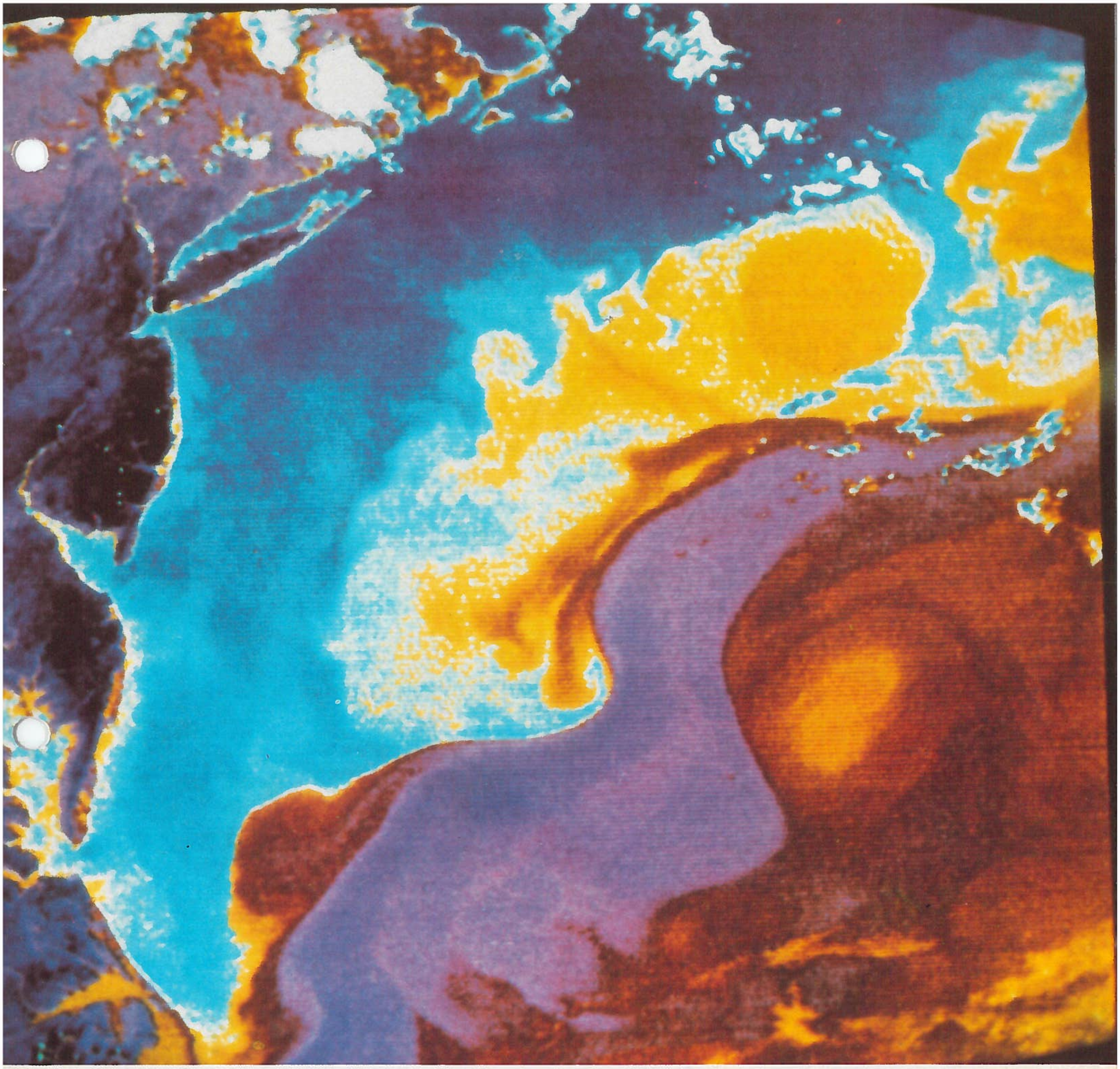






Process of formation of ring Bob (left) was first noted from a series of NOAA-5 infrared satellite images in February and March 1977. In April the research vessel *Knorr* sailed into Bob and detailed study began. (Above and right) cold ring Bob and the Gulf Stream on April 13, 1977. At first ring Bob remained almost stationary but in April Bob became attached to the Gulf Stream and moved quickly downstream. The movement of Bob was tracked (below). Between June and August Bob moved slowly south-west through the Sargasso Sea and in September finally merged with, and disappeared into, the Gulf Stream. Such studies of eddies have provided information for theoretical models which help to explain ocean currents





entrained into the Stream and then into the Sargasso Sea from which it was retrieved in October 1977.

From the study of Bob's life and that of other rings certain patterns emerge. First, rings frequently interact with the Gulf Stream and the interactions are characterized by rapid ring translations downstream in the Stream and by an exchange of water and energy with the Stream. Second, the fate of rings, usually after periods of months or years, is to coalesce completely with the Gulf Stream. Third, the trajectories of rings is complicated and consists of a fast downstream movement when rings are attached to the Gulf Stream and a slower south-westward movement when they are not touching the Stream. Fourth, seafloor topography, including the New England seamounts, influences the path of the Stream and the formation, movement and coalescence of rings.

Because of the difficulties and expense of measuring eddies in the ocean, observation of the dynamics of the ocean is slow. It may be a long time before the eddy transport of energy in the Gulf Stream system can be measured accurately. However, some progress is being made with numerical models of ocean circulation, models that can mimic the real ocean to a surprising degree of accuracy; fast computers are making this possible. The role of the observational oceanographer, the person who discovers and charts the features of the Gulf Stream and other currents, is clear. The task must be to provide the measurements with which the models are developed and against which they are tested. Thus, although charts of the Gulf Stream have changed to describe its eddies more accurately, these charts continue to play a key role in the progress of ocean science today.


GRANADA