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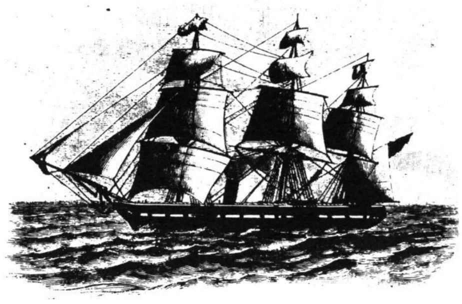

H.M.S. CHALLENGER PREPARING TO SOUND, 1872.

The Oceanography Report
The focal point for physical, chemical, geological, and biological oceanographers.

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Multidisciplinary Program to Study Warm Core Rings

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Warm Core Rings Executive Committee[1]

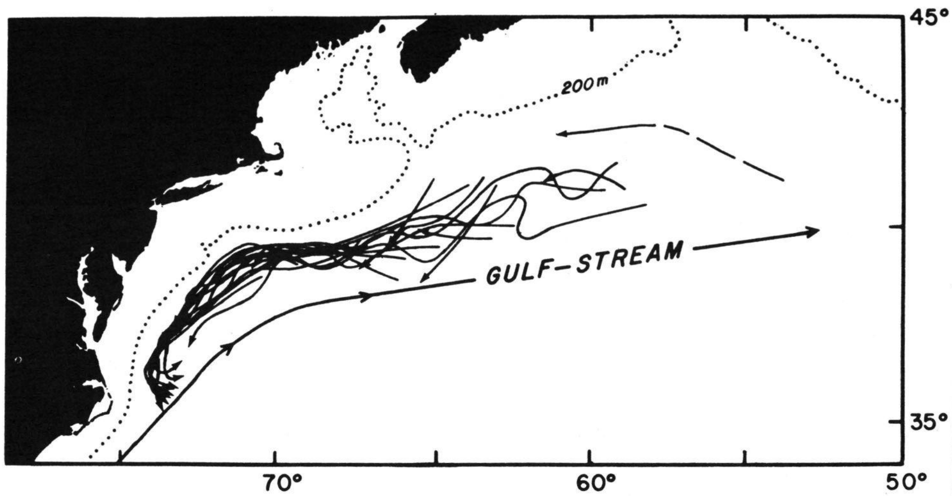

Fig. 2. Inferred warm core ring movement based primarily on an analysis of satellite IR photos for the period 1970–1976. Movement of rings is westward; their mean track is confined between the continental slope and the Gulf Stream. (This illustration was modified from D. Lai and P. L. Richardson's Figure 7, which appeared in the *Journal of Physical Oceanography,* vol. 7, pp. 670–683, 1977, published by the American Meteorological Society.)

A major research program is underway, sponsored principally by the National Science Foundation, to study warm core rings off the East Coast of the United States. The program involves more than 25 principal investigators and 13 different institutions. The National Oceanographic and Atmospheric Administration (NOAA) is actively participating through the National Marine Fisheries Service (NMFS) and their National Earth Satellite Service. NASA is cooperating with aircraft overflights during cruises and by sponsoring some shipboard work.

The program started with its first field operation in September–October 1981. This was a three-ship exercise involving the *Endeavor* from University of Rhode Island, the *Knorr* from Woods Hole, and the *Albatross IV* from NMFS. A series of three, four-ship cruises followed by a final two- or three-ship cruise is in progress during 1982. These cruises will provide a time series of observations during the evolution of one or more rings.

A warm core ring is formed when a meander separates to the north of the Gulf Stream (Figure 1). The resulting ring typically has a diameter of 100–200 km. The central core usually has the physical, chemical, and biological properties of the Sargasso Sea, and a Gulf Stream remnant forms the high velocity region surrounding the core. Streamers of cold shelf and slope water and warm Gulf Stream water are, however, often entrained into the ring circulation (see cover). Satellite infrared images permit us to see rings form, to follow their movements and their interactions with Gulf Stream and with slope water, and to see them coalesce with the Gulf Stream. Warm core rings are the dominant form of oceanographic variability in the slope water off the East Coast of the United States.

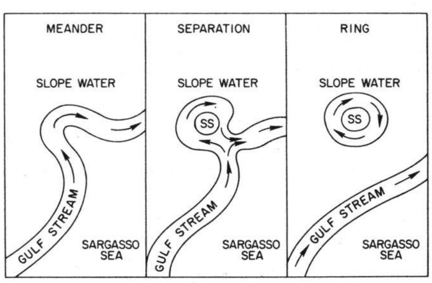

Fig. 1. Three stages in the formation of a warm core ring from a Gulf Stream meander.

[1]David Schink, James McCarthy, Terrence Joyce, Glenn Flierl, Peter Wiebe (vice chairman), Dana Kester (chairman).

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Historical Data

Data from satellites and from ships of opportunity have been used by *Bisagni* [1976], *Halliwell and Mooers* [1979], and *Mizenko and Chamberlin* [1979] to characterize the frequency of occurrence and distribution of warm core rings. One can typically find two to three rings in the slope water at any given time, although there have been periods during the past 5 years with none to as many as nine rings. These rings have mean lifetimes of 6 months. Between the time of separation from and coalescence with the Gulf Stream, most rings migrate (Figure 2) at a rate of 3–5 km/day in a southwesterly direction. They are constrained by the Gulf Stream to the south and east and the continental shelf to the north and west.

Warm core rings are affected by a variety of oceanographic processes. Earlier studies in the northwestern Atlantic showed that during fall and winter, heat loss to the atmosphere generates thermal convection which goes deeper in the ring than in surrounding slope water [*Saunders,* 1971]. *Smith* [1978] estimated that episodic collisions of warm core rings with the shelf/slope front could transport amounts of heat and salt up to 30% of the annual air/sea flux of heat and salt into waters on the continental shelf water off Nova Scotia. Studies in the East Australian Current and the Kuroshio have indicated that warm core rings are formed in these regions also and that they behave analogously.

Program Scope

Our objective is to study the dynamics and evolution of warm core rings in order to understand fundamental oceanic processes in a semi-closed hydrographic regime and to contribute to the understanding of the role rings play in transport and exchange in the region between the shelf water and the Gulf Stream.

An earlier study of cold core rings [*Ring Group,* 1981] showed the need for a well-coordinated program to understand the physical, chemical, and biological interactions occurring in rings. The Warm Core Ring Program is considering several specific questions:

1. What is the physical structure and motion? How are physical processes affected by interactions with surroundings? How does a ring change as it ages?
2. What effect do they have on large-scale chemical transport in the region? Do they enhance vertical fluxes and accelerate biological and chemical interactions?
3. What are the population distributions?

TABLE 1. Principal Investigators and Their Primary Areas of Research in the Warm Core Rings Program

Investigator	Institution	Area of Work
Experimental and Descriptive Physical Oceanography		
Terrence Joyce and Raymond Schmitt	Woods Hole Oceanographic Institution	CTD-O_2 and current profiling and mixing studies
Kevin Leaman and Robert Evans	University of Miami	Loran drifter measurements
Thomas Osborn and Rolf Lueck	Naval Post Graduate School Monterey	turbulent energy dissipation
Chemical Distributions and Processes		
James Bishop	Lamont-Doherty, Columbia University	particulate flux of chemicals
Alfred Hanson and Dana Kester	University of Rhode Island	investigation of trace metal distributions and speciation
Dana Kester and Mary Brown	University of Rhode Island	nutrient and oxygen studies
David Schink and Norman Guinasso	Texas A&M University	radium-radon studies
Biological Investigations: Spatial Patterns		
Richard Backus	Woods Hole Oceanographic Institution	mid-water fish distributions
Patricia Blackwelder	Nova University	coccolithophore abundance and morphology
Greta Fryxell	Texas A&M University	phytoplankton species composition
Ronald Schlitz and David Mountain	National Marine Fisheries Service	fish larvae distributions
Peter Wiebe	Woods Hole Oceanographic Institution	macrozooplankton distribution and life history
Biological Investigations: Plankton Physiology		
Timothy Cowles	Woods Hole Oceanographic Institution	macrozooplankton grazing and egg production
Hugh Ducklow	Lamont-Doherty, Columbia University	bacterial production and biomass distribution
James McCarthy	Harvard	nitrogen nutrient dynamics
Christopher Garside	Bigelow Laboratory, Maine	low level nitrogen dynamics
David Nelson	Oregon State University	silicon nutrient dynamics
Michael Roman	University of Maryland	microzooplankton grazing studies
Theodore Smayda and Gary Hitchcock	University of Rhode Island	phytoplankton growth studies
Analytical and Numerical Modeling		
Glenn Flierl	M.I.T.	circulation and transport modeling
Joseph Wroblewski	Dalhousie University	biological modeling
Remote Sensing		
J. W. Chamberlin	National Marine Fisheries Service	satellite infrared imagery
Wayne Esaias	NASA	aircraft remote sensing of ocean waters
Don Olson and Otis Brown	University of Miami	remote sensing sea surface temperature and color
Charles Yentsch and Raymond C. Smith	Bigelow Laboratory, Maine, University of California, Santa Barbara	remote sensing of biologically important parameters

How do they relate to environmental factors in the ring, particularly as it matures? What controls primary production and activity at higher trophic levels within the ring?

This program has the following main components: (1) experimental and descriptive physical oceanography, (2) enhancement and application of remote sensing to ocean studies, (3) chemical distributions and processes, (4) biological spatial patterns, (5) effect of entrainments on fish populations, (6) plankton physiology, and (7) analytical and numerical modeling.

The investigators in this program are listed in Table 1 according to the primary component with which they are associated; however, some contribute to more than one component.

First Cruise

The program started with a three-ship (R/V *Atlantis II*, R/V *Endeavor*, R/V *Albatross IV*) expedition in September–October 1981. The ring studied was the fourth warm ring observed to form in the slope water region in 1981 and was denoted 81-D (see cover). The first analyses of these observations were presented at a joint AGU/ASLO meeting in San Antonio, Texas, in February 1982 (*Eos*, p. 51, January 19, 1982, abstracts from session, Physics, Chemistry, and Biology of Gulf Stream Rings). These findings have substantially modified our perceptions of the rings. Rings can have complex life cycles that may involve repeated interactions with the Gulf Stream. For exmple, during the period of study, 81-D underwent a major interaction with the Gulf Stream during which both a decrease in ring diameter and a shoaling of the thermocline by nearly one-third occurred. During this interaction, two major entrainments were observed. A tongue of warm water from the Gulf Stream spiralled into the ring from the west side. Surprising excesses of radon were found within the ring core from 20 to 250 m deep, indicating some of these waters had been proximate to sediments within the past few weeks. A second tongue of about 180 km^3 of shelf water was drawn into the ring on the east side. During a 1-week period of intense gales and the entrainment events, the upper 100 m of the ring core gained substantial amounts of dissolved oxygen as a result of air-sea exchange and photosynthetic production. There also was a vertical flux of nutrients to the euphotic zone that stimulated new production and resulted in an overall decrease in nitrate in the upper 100 m. These changes did not occur in the slope water outside the ring.

Warm core rings were postulated to have a core of biologically poor Sargasso Sea water, slowly changing in population abundance and species composition to that of the slope water as the ring matured. In fact, the ring core was found to be rich in biota. Chlorophyll, primary productivity, biogenic silica, particulate carbon, and particulate nitrogen were higher in the center than in slope water. Zooplankton biomass measurements showed the ring core to be as rich as the surrounding waters.

1982 Time Series

The first cruise of the 1982 time series was completed May 10, 1982. This was a joint ship operation involving the R/V *Knorr*, the R/V *Oceanus*, R/V *Endeavor*, and R/V *Albatross IV*. NASA conducted two aircraft overflights for chlorophyll, sea surface temperature, salinity, and ocean surface waves spectra using a variety of airborne sensors.

Infrared images revealed the formation of ring 82-B in late February. Ship of opportunity XBT observations in March showed the ring core to have temperatures between 17° and 18°C to depths of 300 m. By late April, the core had been cooled to temperatures less than 16°C and was mixed uniformly to approximately 450 m. Although core waters of this ring were of Sargasso Sea origin, major transformations in the biological and chemical constituents had already occurred. Major nutrients (nitrate, silicate, and phosphate) were present in substantial quantities to the surface, a situation rarely observed in the Sargasso Sea. In addition, a number of phytoplankton and zooplankton species typical of slope water and shelf water were present within ring core waters. The ring had very low chlorophyll concentrations relative to the adjacent high velocity region and slope water apparently because of the lack of stratification in the surface waters.

Each of the three NSF-funded vessels carried out complementary tasks in this coordinated study. R/V *Endeavor* was responsible for expendable bathythermograph traces (XBT) star surveys of the temperature field of the ring and for mapping vertical structure of horizontal currents to 100 m using an acoustic Doppler current profiling system. Continuous measurements were also made of temperature, salinity, chlorophyll, and other accessory plant pigments and transmissivity of the surface waters. Detailed CTD-O_2 profiles to the sea floor were made on transects across the ring and on transects upstream and downstream of the ring from the continental shelf out into the Sargasso Sea. Bio-optical profiles were also made at each station, which included separate determinations of temperature, salinity, as well as chlorophyll, fluorescence, transmissivity, downwelling and upwelling spectral irradience and nutrients.

Most of the experimental biological and chemical work was conducted aboard the R/V *Knorr.* Fourteen major stations were occupied for periods of 12–48 hours, during which time CTD-O_2 rosette casts using 5-l and 30-l bottles were made to obtain water for use in studies of phytoplankton species composition, bacterial enumeration, and physiological studies. The latter included studies of the incorporation of ^{14}C, ^{15}N, ^{33}P, and ^{30}Si labeled nutrients, thymidine uptake by bacteria, and trace metal distributions. Net collected zooplankton and bottle collected microzooplankton were used in grazing experiments. Chlorophyll profiles were determined in the upper 100 m from pumped samples.

Spatial mapping of macrozooplankton and midwater fish was carried out on board the R/V *Oceanus* at eight stations extending from the ring center to the slope water, using MOCNESS net systems with 1 m^2 and 20 m^2 nets. The 1 m^2 system obtained depth specific samples at 100 m intervals from 1000 m to 200 m and 25 m intervals from 200 m to the surface. The 20 m^2 system obtained depth specific samples at 250 m intervals from 1000 m to the surface. In addition, large volume pumping for particulate matter at 8 depths from the surface to 700 m, chlorophyll casts generally to 100 m (occasionally to 200 m), and shallow (upper 600 m) and deep (deep-sea floor to an altitude of 600 m) casts for radon 222, radium 226, and radium 228 were made at these stations. The latter samples were collected with 30-l niskin bottles deployed on the hydrowire or on a CTD/rosette system which also contained an in situ pumping system for the extraction of radium 228.

R/V *Albatross IV* concentrated on the physical and biological description of the shelf water entrained to the west of 82-B. Vertical CTD-O_2 profiles to 1000 m and plankton hauls in the upper 100 m were made on transects across the feature. There were also continuous underway measurements of temperature, salinity, and chlorophyll. In addition, an array of seven current meter moorings were set at the edge of the continental shelf along the northern side of 82-B and in the entrainment feature.

Summary of Warm Core Ring Findings to Date

1. Satellite and aerial remote sensing provide quantitatively useful information on the temperature and chlorophyll structure and characteristics of warm core rings.
2. In many instances, we have seen larger changes in the physics, chemistry, and biology of a ring in a week's time than we had expected would occur in several weeks. These changes were associated with Gulf Stream interactions, and cold water zooplankton species invading the ring. The cold water species had high physiological rates compared to their warm water counterparts. Large chemical fluxes have been seen in the center of the ring.
3. Stratification in the water column and its variation with time plays a very important role in chemical and biological processes in a ring.
4. There were substantial upward shifts in the zooplankton biomass of 82-B between March and May. These shifts are observed in the slope water, but they do not occur in the Sargasso Sea.
5. Significant amounts of shelf water and associated organisms can be advected in entrainment features.

This interdisciplinary research program is substantially increasing our knowledge of the processes associated with warm core rings.

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